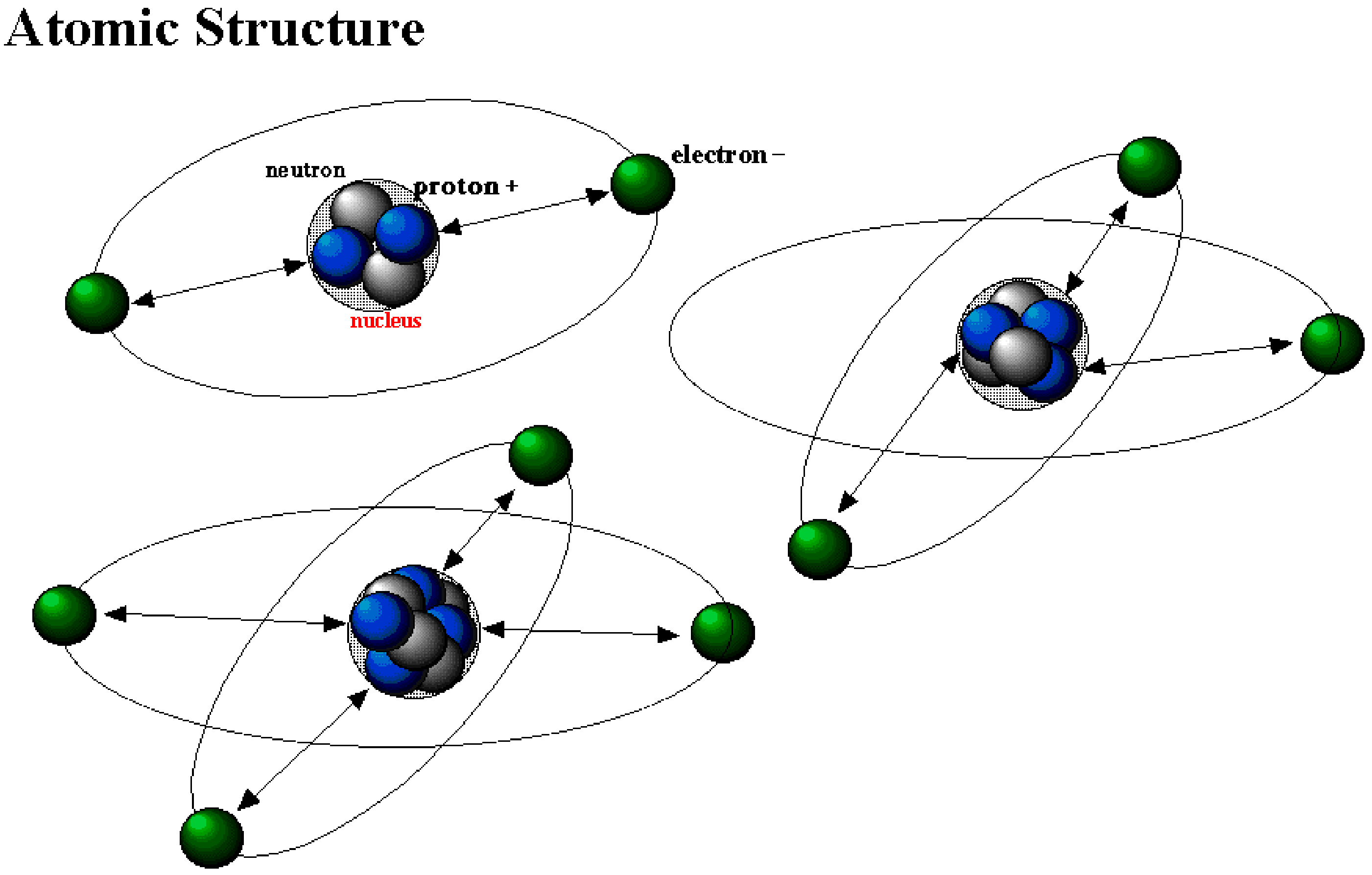
RADIATION PHYSICS

By . Youssef Gamal

Atomic structure

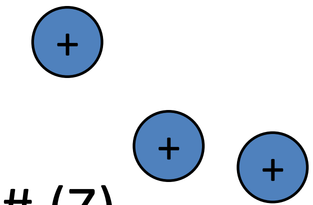


The Atomic Nucleus

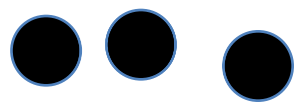
- Protons

  +ve Charges

  # protons = atomic # (Z)

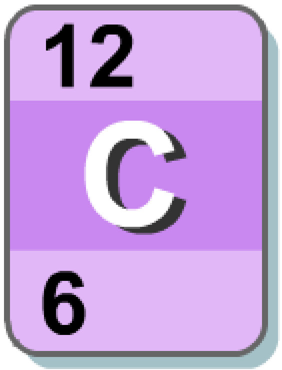


- Neutrons
  - No charge
  - Mass about the same as proton



The atoms of any particular element always contain the same number of protons and so the same atomic number. For example:

- hydrogen atoms always contain 1 proton
- carbon atoms always contain 6 protons
- magnesium atoms always contain 12 protons.



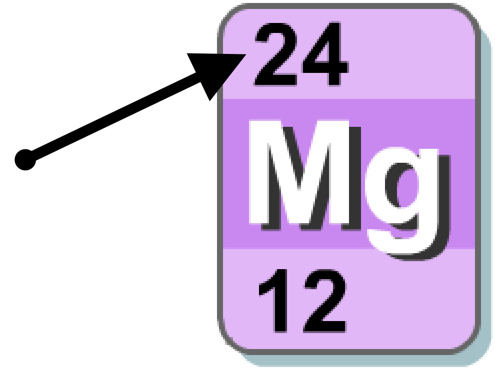
Atomic number is the smaller of the two numbers shown in most periodic tables.

If the number of protons changes, then the atom becomes a different element.

What is mass number?

mass number = number of protons + number of neutrons

The sum of the protons and neutrons in an atom's nucleus is the mass number. It is the larger of the two numbers shown in most periodic tables.



Atoms	Protons	Neutrons	Mass number
hydrogen	1	0	1
lithium	3	4	7
aluminium	13	14	27

Orbital Electrons

- Electrons

  -ve charges

  very small mass compared with protons / neutrons

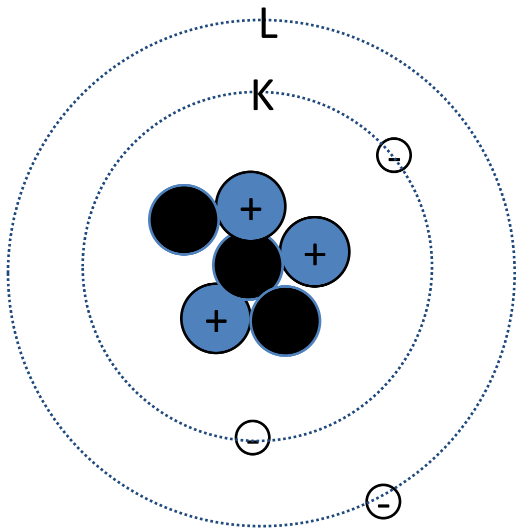
- Electrons reside <u>only</u> at certain energy levels or ***Shells***

  Designations start at K shell

    K shell closest to nucleus

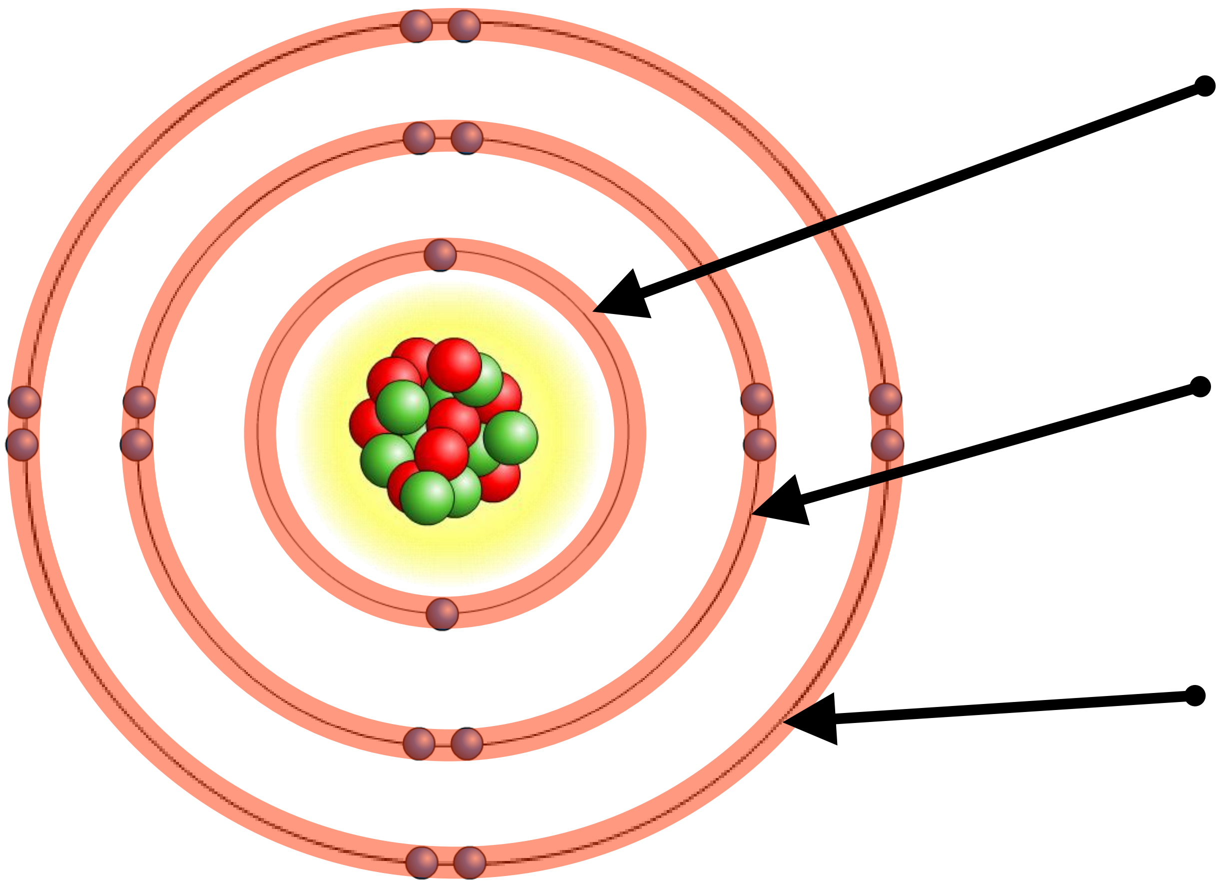
    L shell next closest

    Shells proceed up from K, L, M, N, etc.



How many electrons per shell?

Each shell has a maximum number of electrons that it can hold. Electrons will fill the shells nearest the nucleus first.



1st shell holds a maximum of 2 electrons

2nd shell holds a maximum of 8 electrons

3rd shell holds a maximum of 8 electrons

Outermost shell = valence shell (responsible for thermal & electrical properties)

No valence shell can have more than 8 electrons

How many electrons?

Atoms have no overall electrical charge and are neutral.

This means atoms must have an equal number of positive protons and negative electrons.

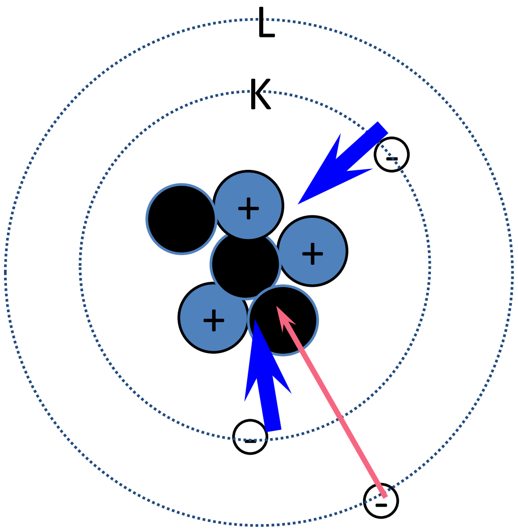
The number of electrons is therefore the same as the atomic number.

Atoms	Protons	Neutrons	Electrons
helium	2	2	2
copper	29	35	29
iodine	53	74	53

	mass	charge
proton	1	+1
neutron	1	0
electron	almost 0	-1

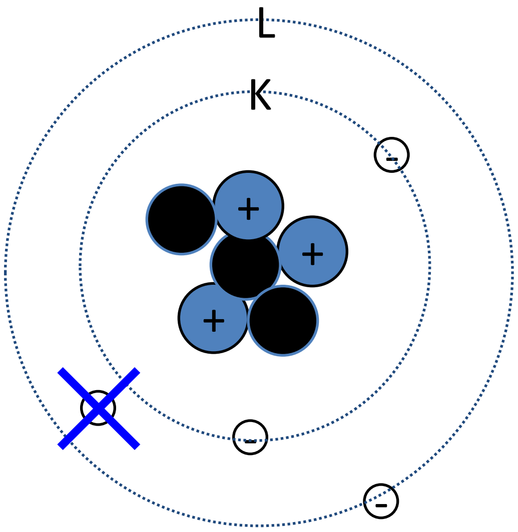
Binding Energy

- energy required to remove orbital electron from atom
- Negative electrons attracted to positive nucleus
- more binding energy for shells closer to nucleus
  - K shell has highest binding force (E_K is more than E_L)
- higher atomic # materials (higher Z) result in more binding energy
  - more positive charge in nucleus
  - E_K of tungsten (Z=74) is more than E_K of aluminium (Z=13)

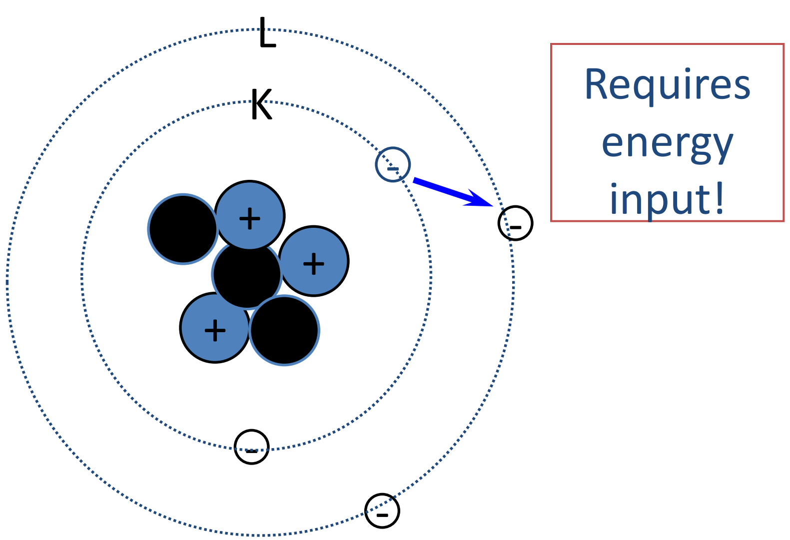


Electron Shells (cont.)

- Electrons can only reside in a shell
  - electron has exactly the energy associated with its shell
  - electrons attempt to reside in lowest available energy shell

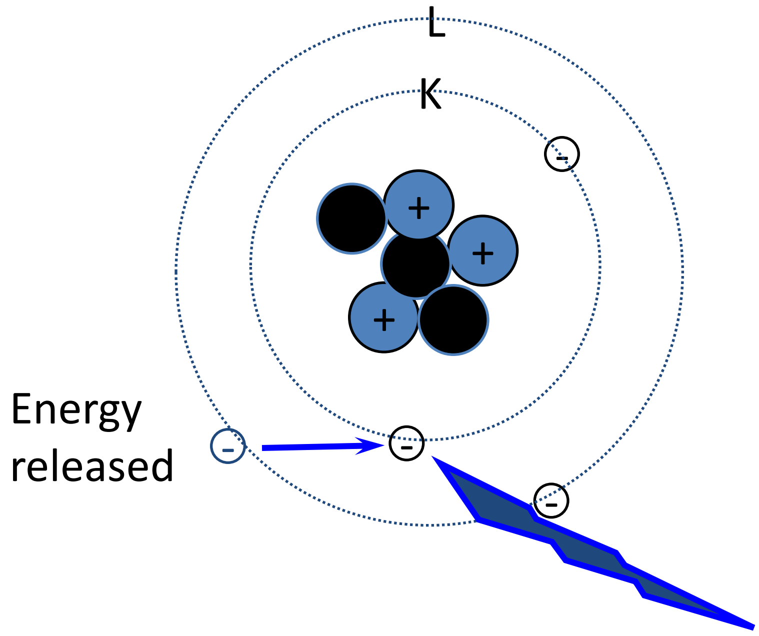


- Electrons can move from shell to shell
- To move to higher energy shell requires energy <u>input</u> equal to difference between shells

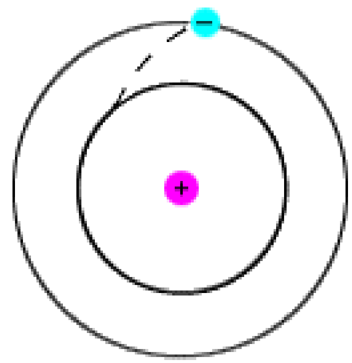


- to move to a lower energy shell requires the release of energy equal to the difference between shells

=characteristic x-rays



Excited atom = atom with an electron raised from on shell to another



Excited State

Fate of excited atom : the electron will fall back releasing energy

Energy is released as : QUANTUM OF PHOTONS

The units used in our curriculum

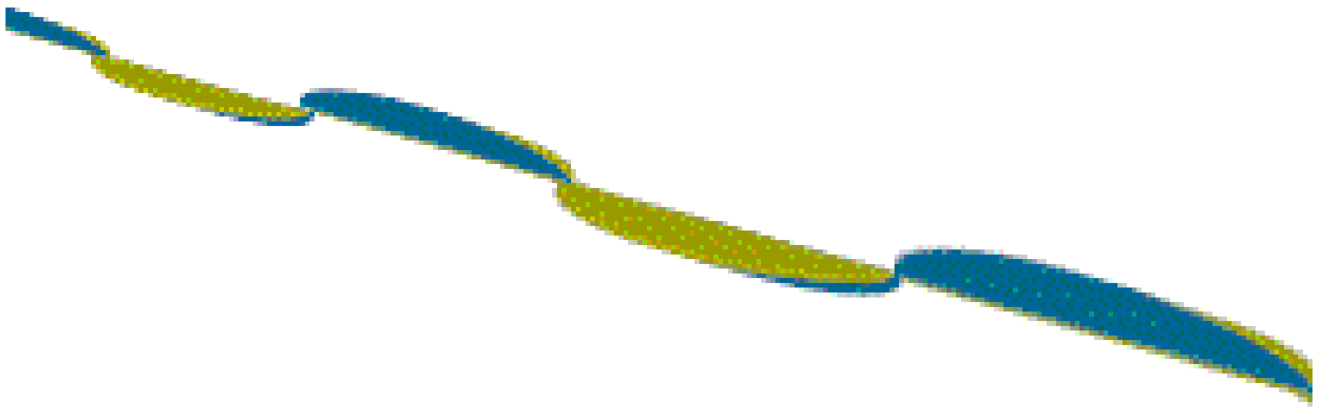
- Unit of energy = joule
- Unit of electrical charge = coulomb (C)

  Electrical charge of electron = 1.6×10^{-19} C
- Unit of electrical potential = volt

  Volt = electrical potential required for 1C to acquire 1 joule

- Joule is a very large Unit to describe the energy of photon
- electron volt (eV) = energy acquired by electron when accelerated at potential difference of 1V
- So ……. eV = 1.6×10^{-19} J.

Electromagnetic waves



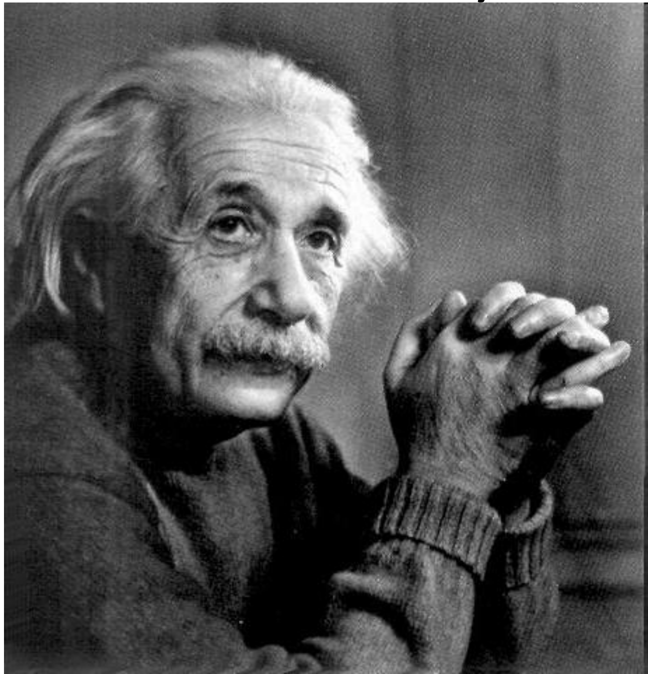
Electromagnetic waves

- Produced by the movement of electrically charged particles
- Can travel in a "vacuum" (they do NOT need a medium
- Travel at the speed of

  light $= 3 \times 10^{8}$ m/s (ms^{-})

Wave-particle Duality

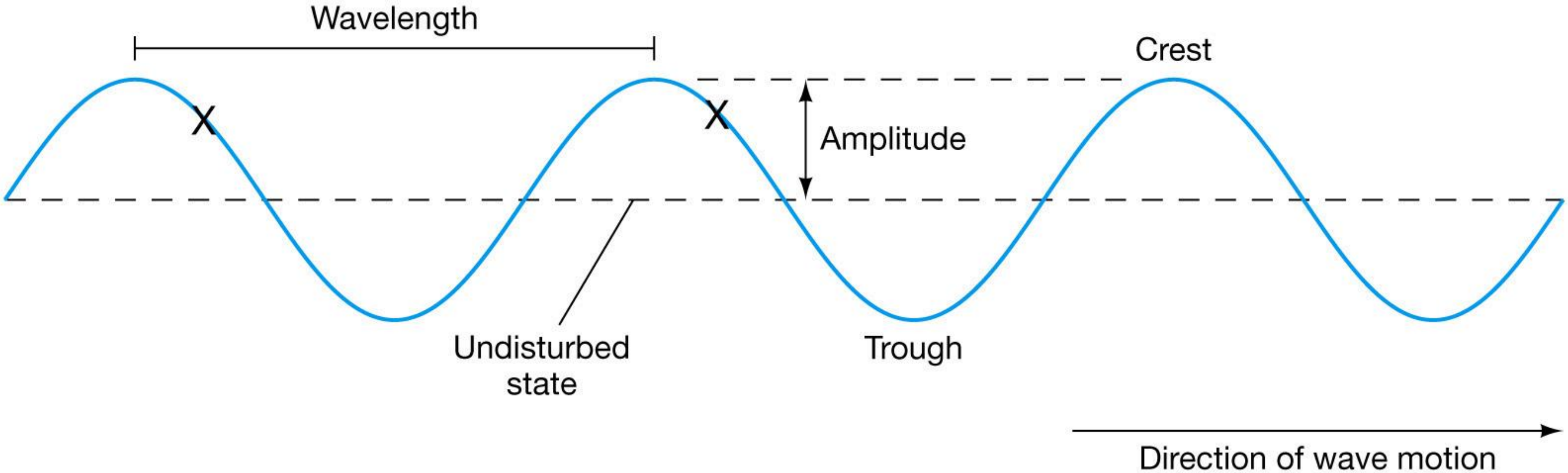
- EM waves can behave like a wave or like a particle
- A "particle" of EM wave is called a photon (the smallest quantity of any type of EM radiation)
- PHOTONS HAVE NO MASS AND NO CHARGE



Wave Terminology

- ***Wavelength*** - distance between two like points on the wave
- ***Amplitude*** - the height of the wave compared to undisturbed state

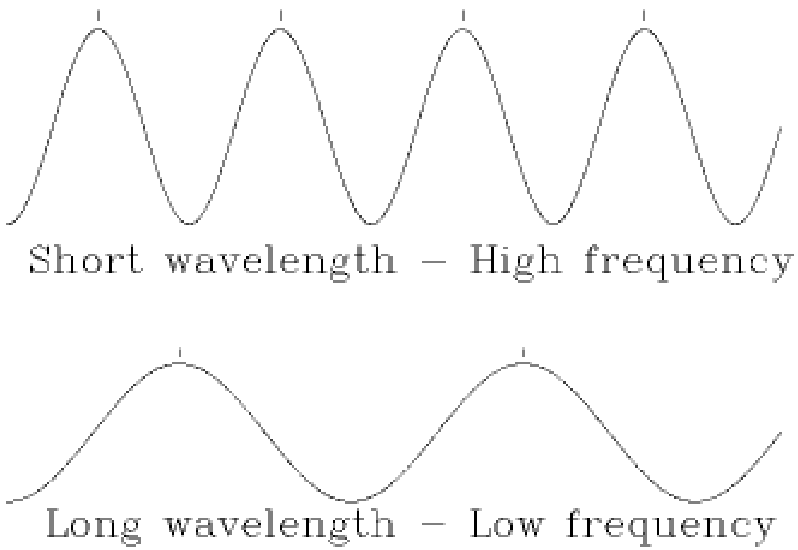
- ***Period*** - the amount of time required for one wavelength to pass
- ***Frequency*** - the number of waves passing in a given amount of time (Measured in hertz)



Wave Relationships

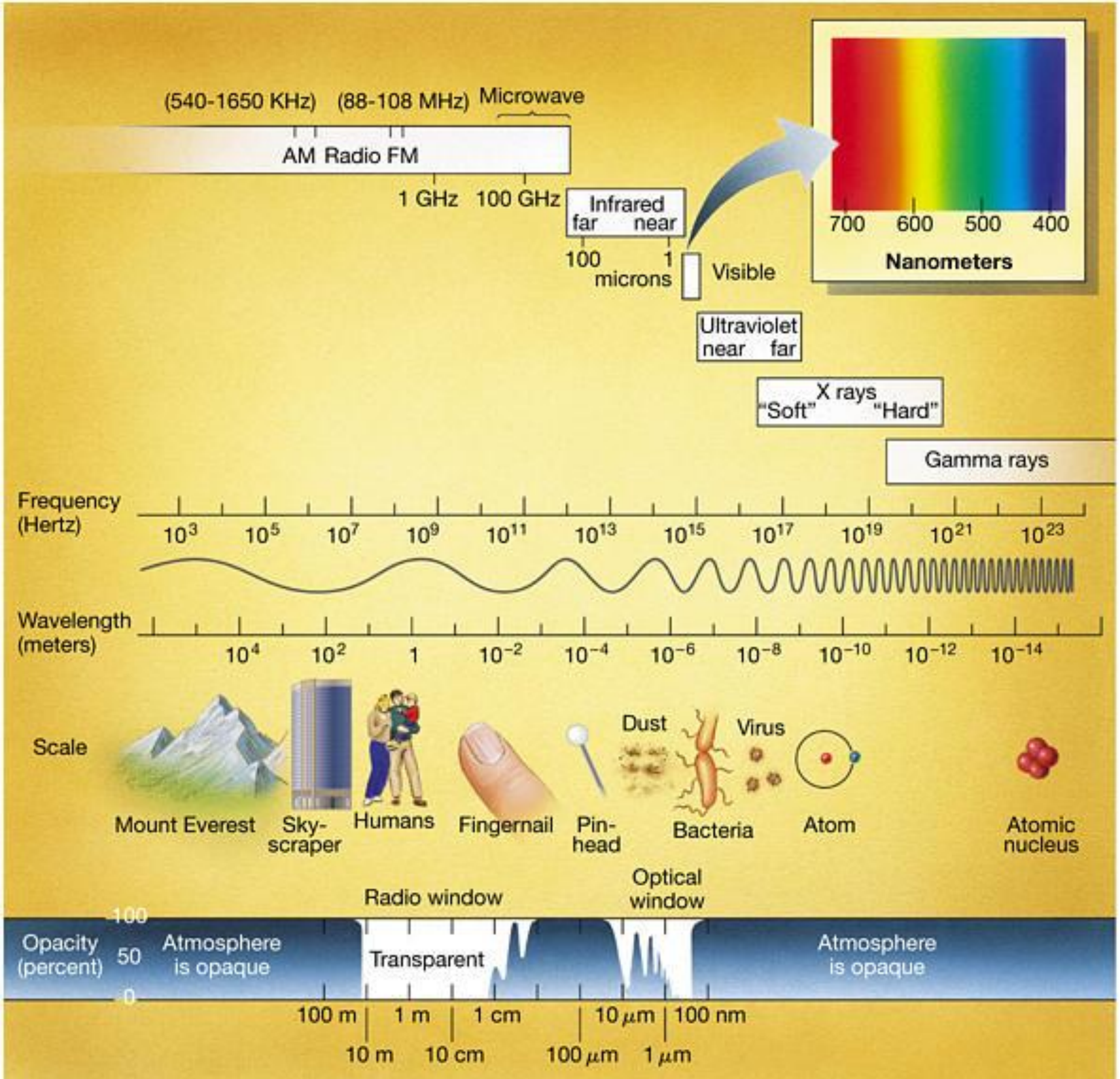
$$frequency = {}^{1}\!/_{period}$$

$$velocity = \frac{wavelength}{period} = wavelength \times frequency$$



- Photon energy is proportional to the frequency
- E= h x frequency

  (h = planck’s constant)


(540-1650 KHz)
(88-108 MHz)
Microwave
AM Radio FM
1 GHz
100 GHz
Infrared
far near
100
1
microns
Visible
700 600 500 400
Nanometers
Ultraviolet
near far
X rays
"Soft" "Hard"
Gamma rays
Frequency (Hertz)
10^3 10^5 10^7 10^9 10^{11} 10^{13} 10^{15} 10^{17} 10^{19} 10^{21} 10^{23}
Wavelength (meters)
10^4 10^2 1 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14}
Scale
Mount Everest
Sky-scraper
Humans
Fingernail
Pin-head
Dust
Bacteria
Virus
Atom
Atomic nucleus
Radio window
Optical window
Opacity (percent)
100
50
0
Atmosphere is opaque
Transparent
Atmosphere is opaque
100 m
10 m
1 m
10 cm
1 cm
100 μm
10 μm
1 μm
100 nm

Beam intensity

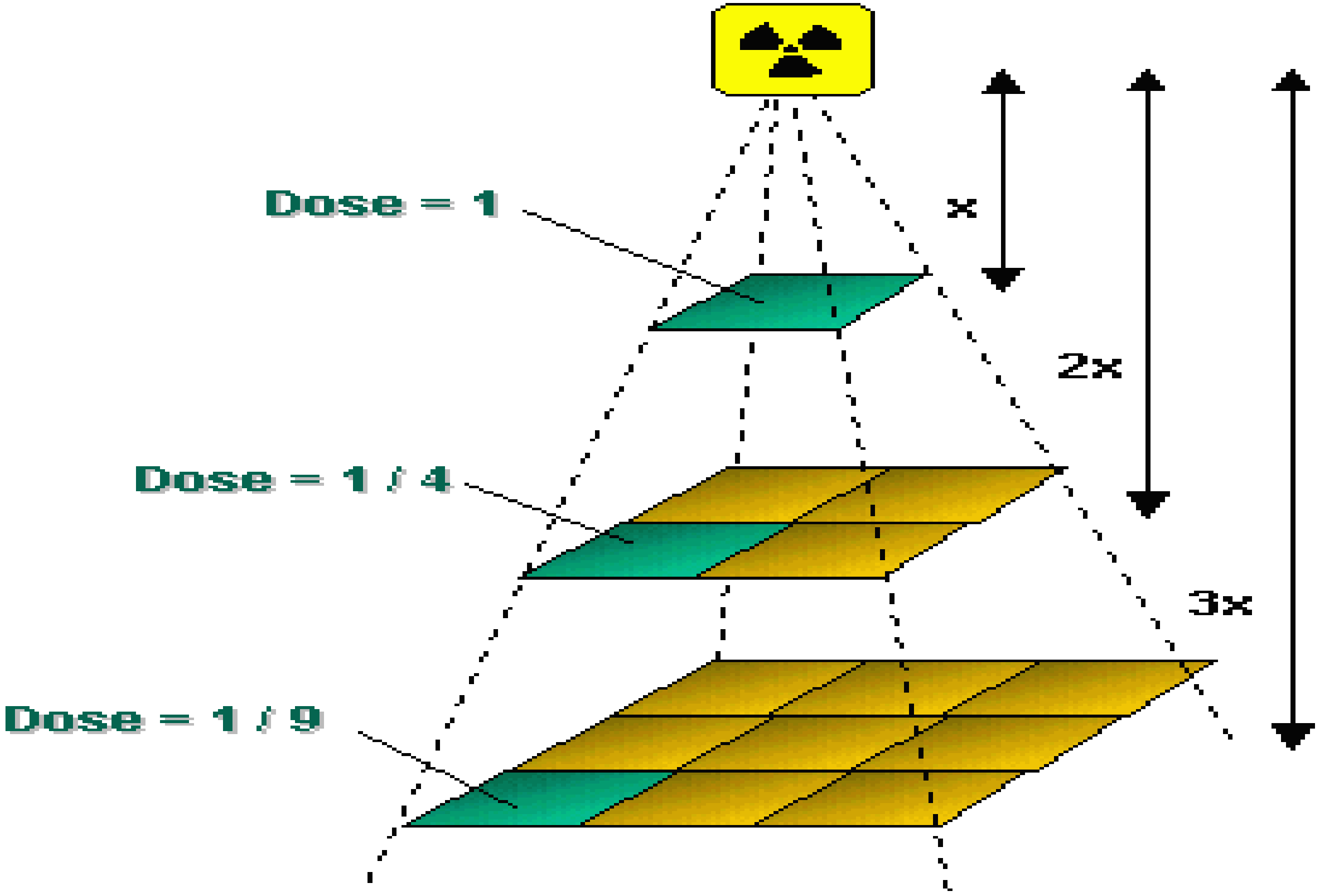
- Total number of energy per unit area passing through cross section per unit time
  = energy fluence rate
- Intensity is proportional to the square of the amplitude

Inverse Square Law

- When radiation is emitted from a source the intensity decreases rapidly with distance from the source

- The decrease in intensity is inversely proportional to the square of the distance of the object from the source

Intensity Is Spread Out



Inverse Square Law

- Doubling the distance decreases intensity by a factor of four.
- To apply this law .. There must be no scatter or absorption of radiation

Inverse Square Law Formula

Intensity #1

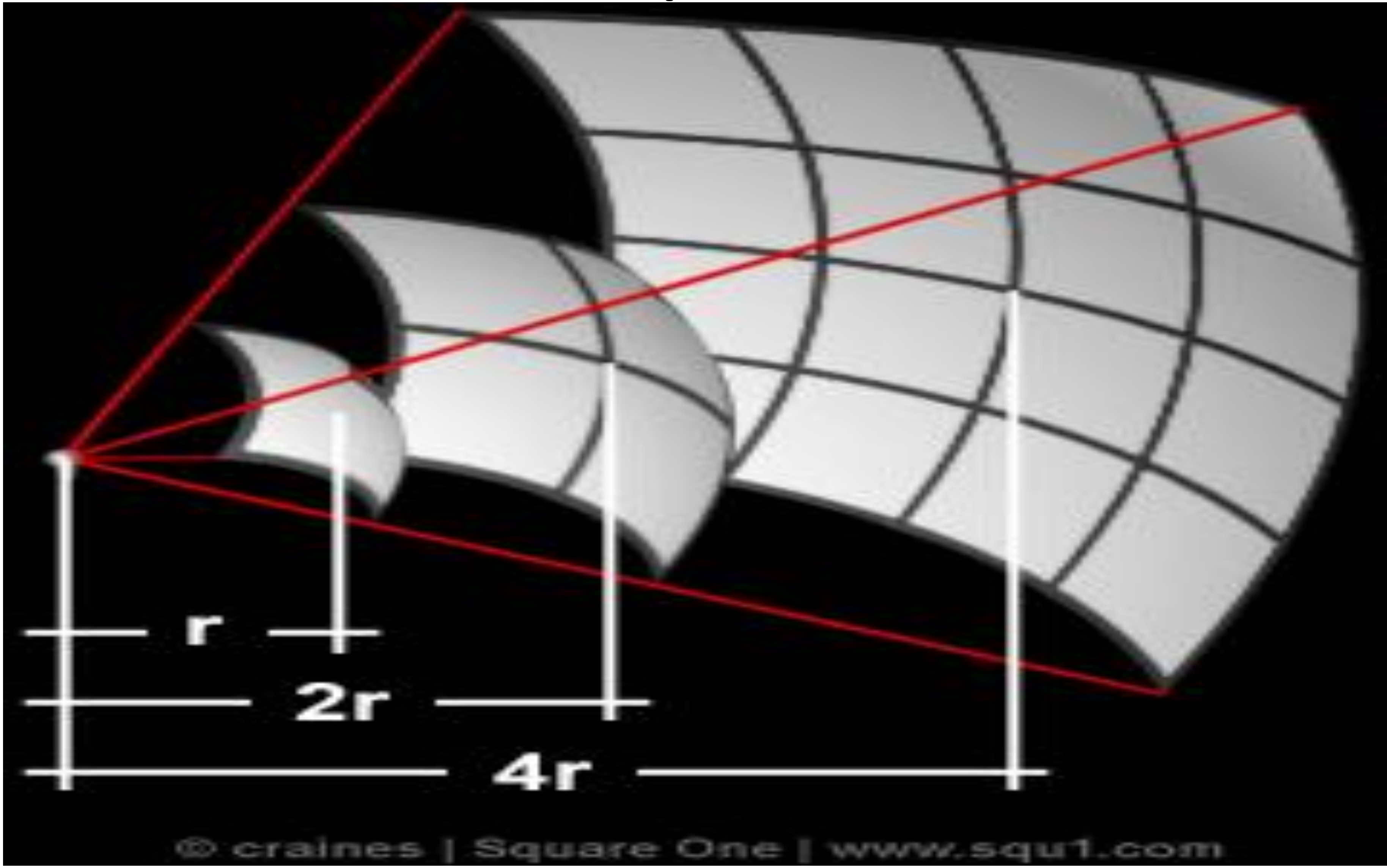
Intensity #2

$$\frac{I_1}{I_2} = \frac{{d_2}^2}{{d_1}^2}$$

Distance #2 - Squared

Distance #1 - Squared

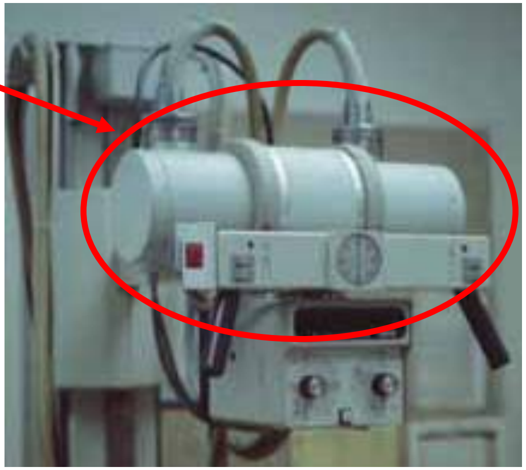
Inverse Square Law

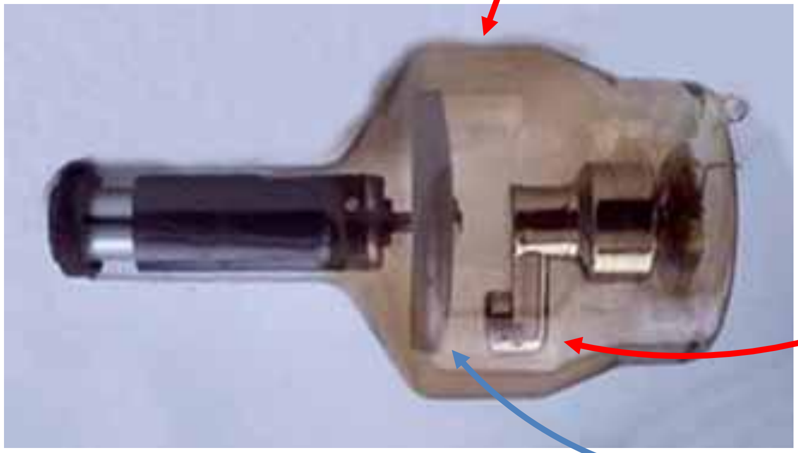


X-Ray production and Tube Construction

X-Ray Tube Components

- Housing
  - Visible part of tube
- Glass Enclosure
  - Vacuum
  - Electrodes
    - Cathode (-ve)
      - Filament
    - Anode (+ve)
      - Target





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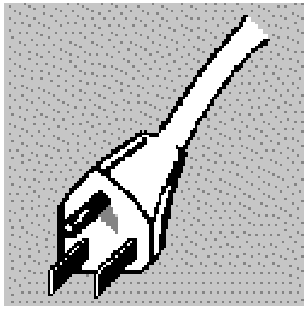
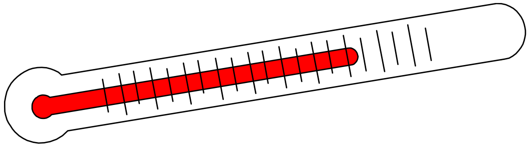
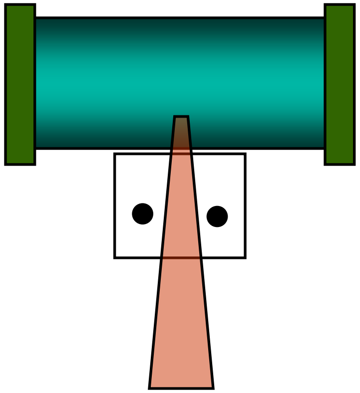
X-Ray Tube



- Converts Energy
  - <u>FROM</u>
    - electrical energy
  - <u>To</u>
    - Heat



      - > <u>99%</u> of incident energy
      - Bad! Ultimately destroys tubes
    - X-Rays
      - < <u>1%</u> of incident energy
      - Good! Our desired product



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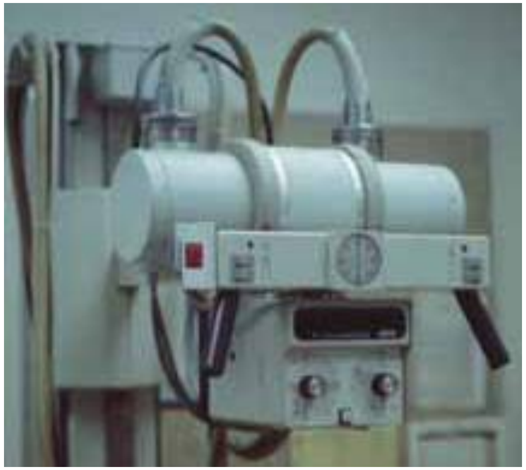
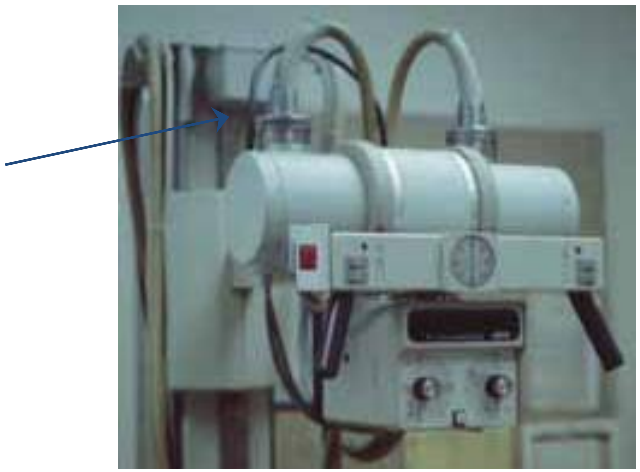
Tube Housing

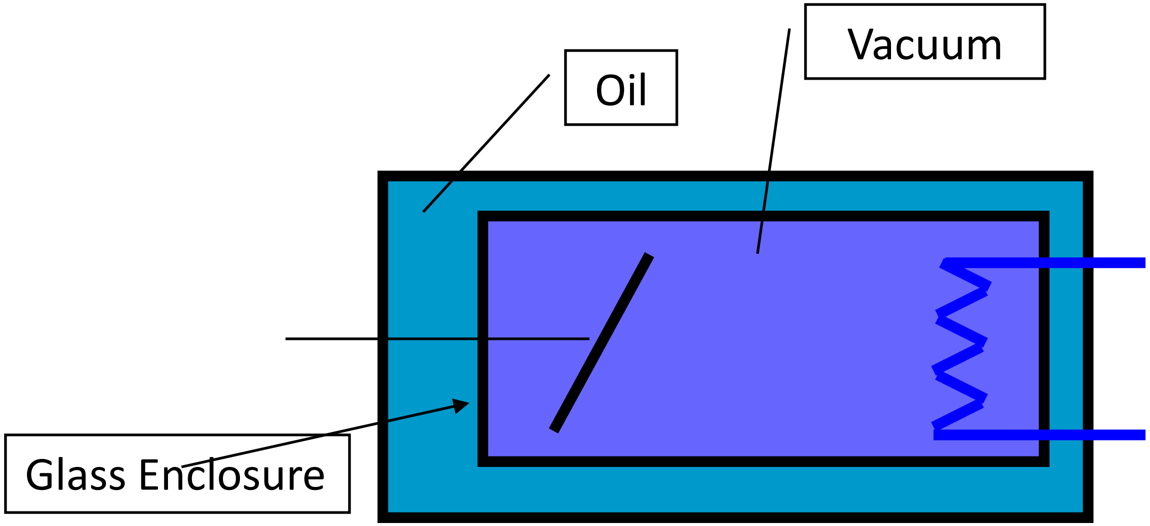
- Shields against leakage radiation
  - lead lined



Tube Housing (cont.)

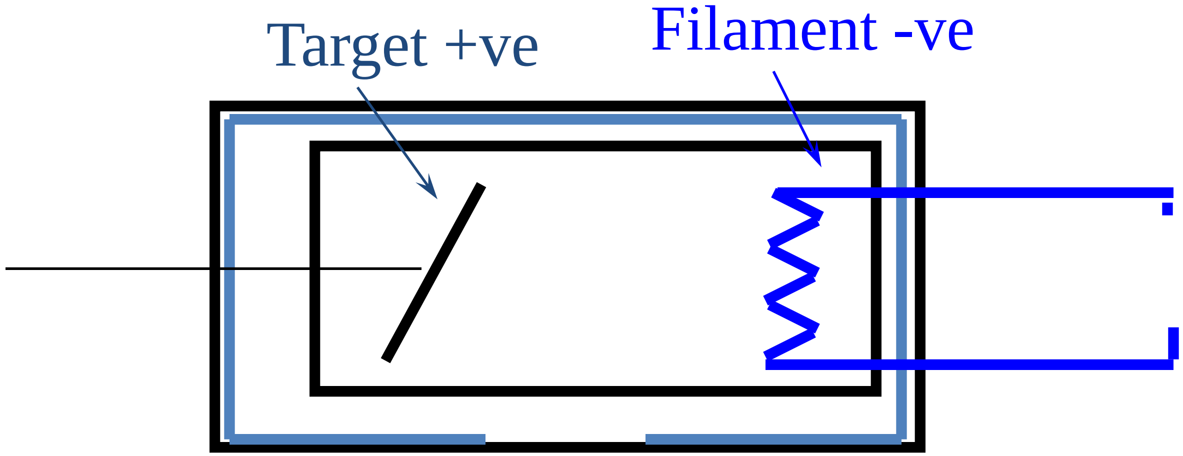
- housing filled with oil
  - cools
  - electrical insulation





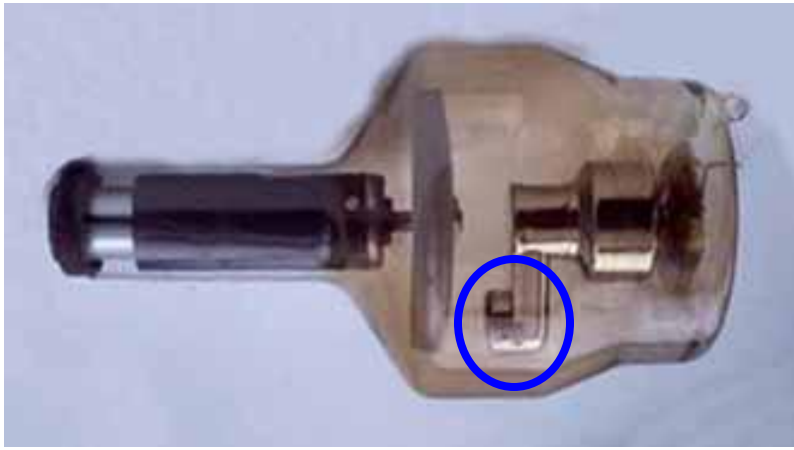
Inside the Glass Insert

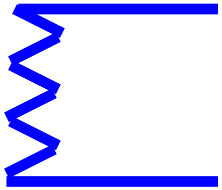
- Filament = cathode (-ve charge)
- Target= anode (+ve charge)



Cathode (filament)

- Coil of tungsten wire
  - similar to light bulb filament
- Tungsten advantages
  - high melting point
  - little tendency to vaporize
  - long life expectancy





THERMIONIC EMISSION

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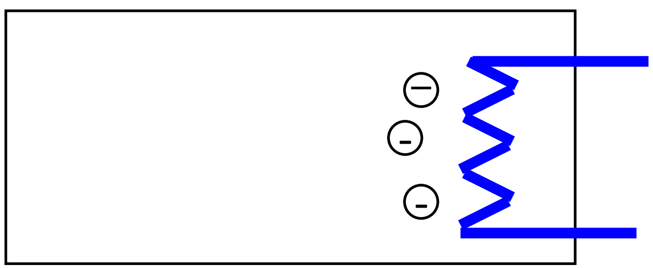
- Filament is heated by passing electrical current through it to a temperature at which it is white hot (2200°C)
  - Some electrons gain energy and leave the material surface (become free)



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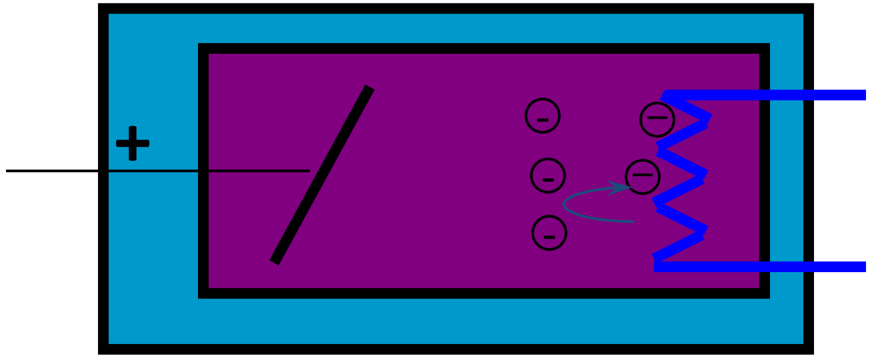
Space Charge

- Electrons leave filament
  - filament becomes positive
    - Negative electrons stay close
- Electron cloud surrounds filament
- Cloud repels new electrons from filament and Limits electron flow from cathode to anode



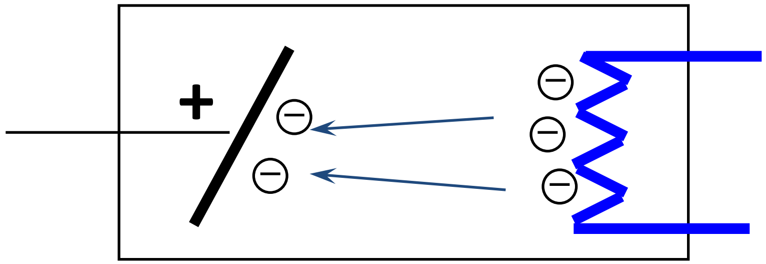
TARGET

Usually tungsten is used

HIGH Z# (74)------EFFICIENCY OF X-RAY PRODUCTION

HIGH MELTING POINT (TARGET HEATED TO 2,000 ° C)

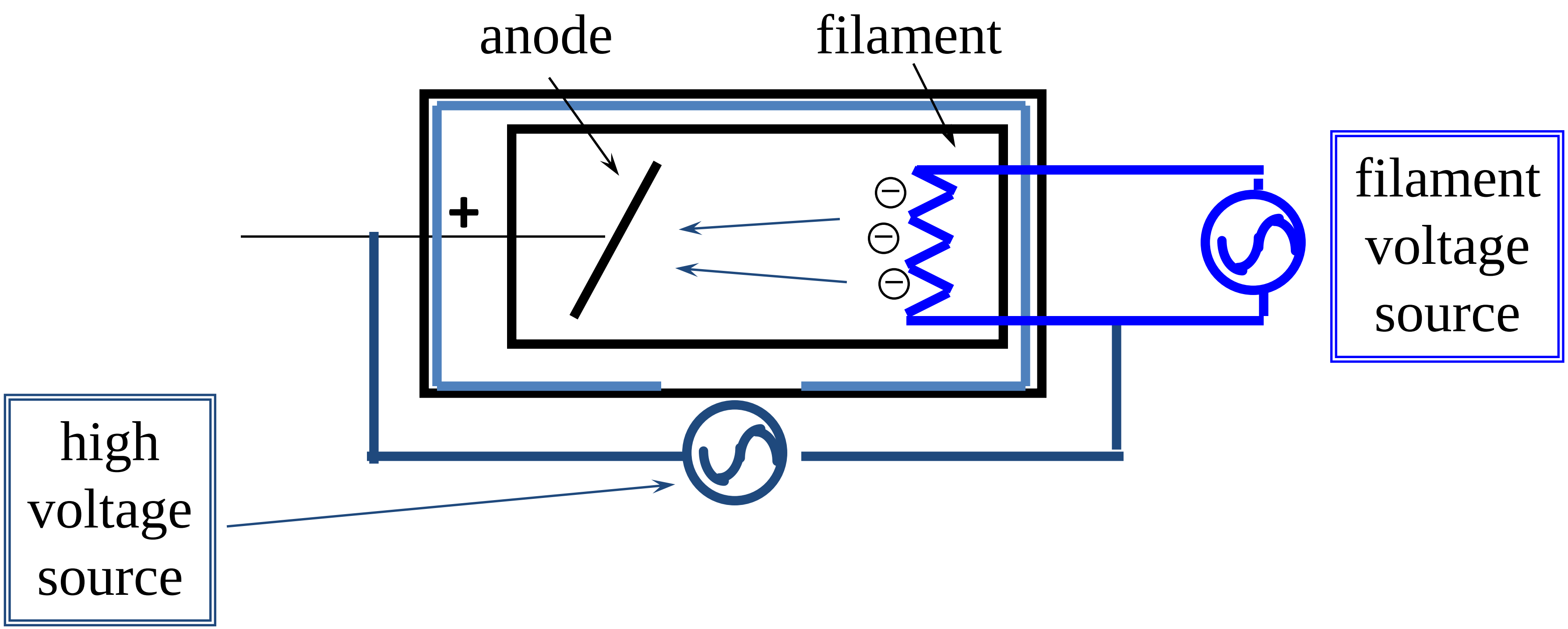
* Kilovoltage and milliamperage



- Positive (high) voltage applied to anode relative to filament
  - electrons accelerate toward anode target
    - Gain kinetic energy
  - electrons strike target
    - electrons' kinetic energy converted to
      - heat
      - x-rays

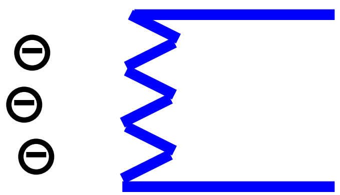
Requirements to Produce X-Rays

- Filament Voltage
- High Voltage



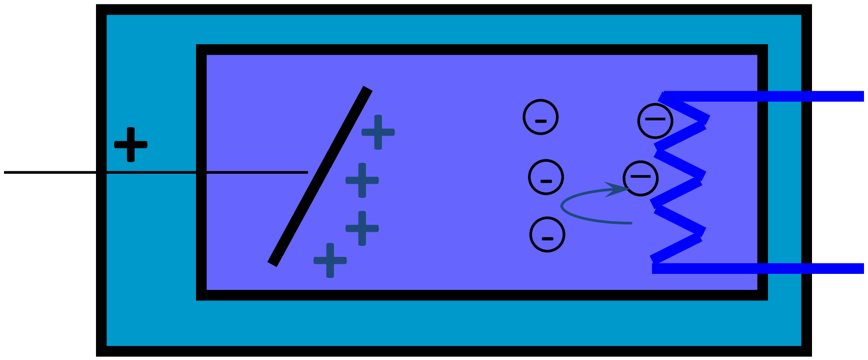
Cathode (filament)

- filament heated by electric current
  - ~ 10 volts
  - ~ 10 amps
- <u>Filament</u> current is <u>**not**</u> tube current
- <u>filament</u> voltage is <u>**not**</u> tube voltage



Tube Kilovoltage

- = accelerating voltage between cathode and anode
- 30-150 KV



- raising kilovoltage gradually overcomes space charge
  - Free electrons are repelled be –ve cathode and attracted by + ve anode
  - Travel in vacuum by half of light speed to bombard anode
- At high enough kilovoltage **saturation** results
  - All electrons liberated by filament reach target
- Raising kilovoltage further has no effect on # electrons reaching anode

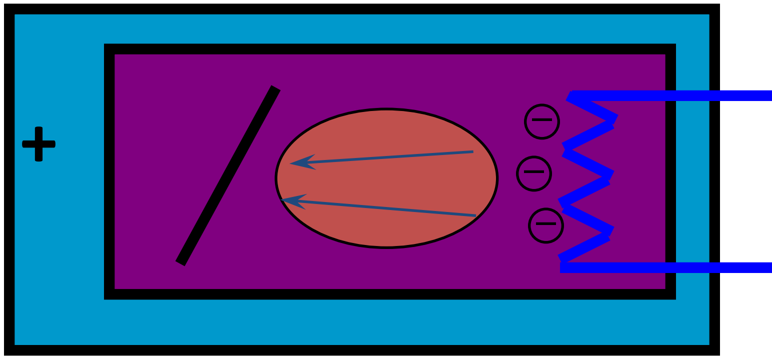
Tube Current (mA)

- <u>Rate</u> of electron flow from filament to target
  - Electrons / second
- Measured in **milliamperes** (mA)
- 0.5 – 1000 mA

Limited by

- Filament voltage and current and thus filament temperature (small increase in temperature →large increase in tube current)

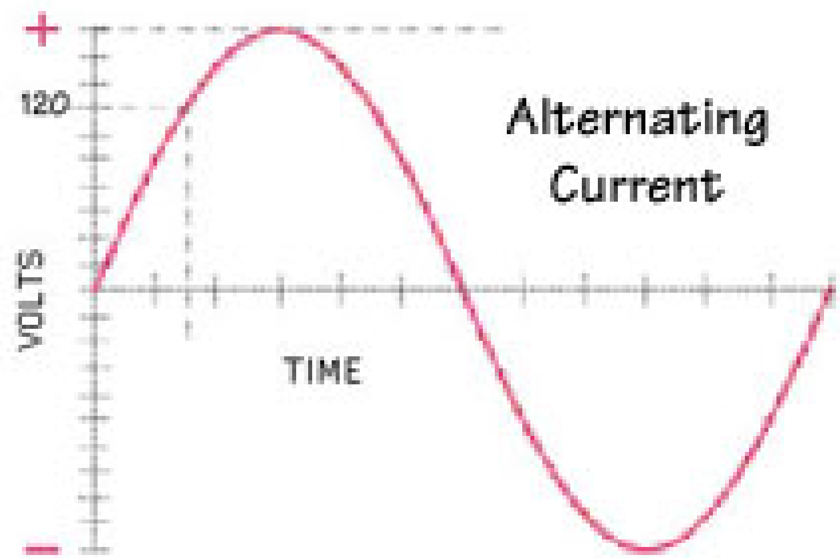
CHANGING TUBE VOLTAGE DOSE NOT AFFECT TUBE CURRENT



X-Ray Generator

- Supplies electrical power to x-ray tube
  - high voltage between anode & cathode
  - filament voltage
- Controls exposure timing
  - Turns exposure on and off

Alternating current (AC) supply (mains)

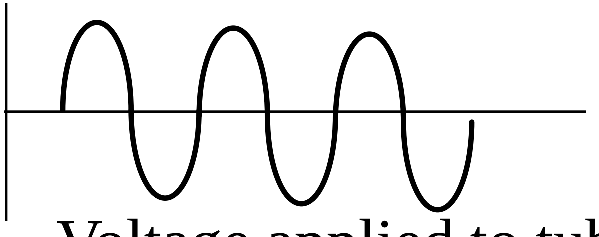


Not suitable for x ray production

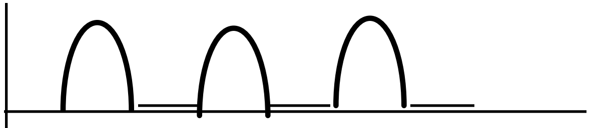
Solution is Rectifaction = converting –ve part of the waveform into +ve Kv

Self Rectified Circuit

- X-Ray tube acts as rectifier
- = single phase have wave rectified
- Rarely seen (only in dental radiology)

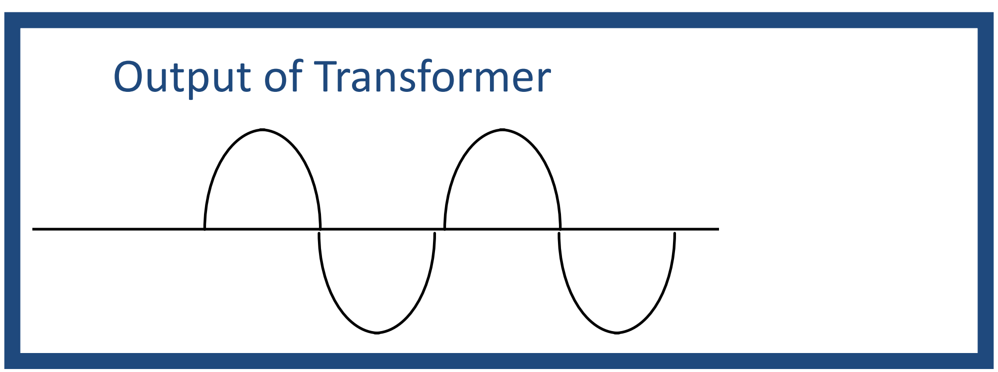


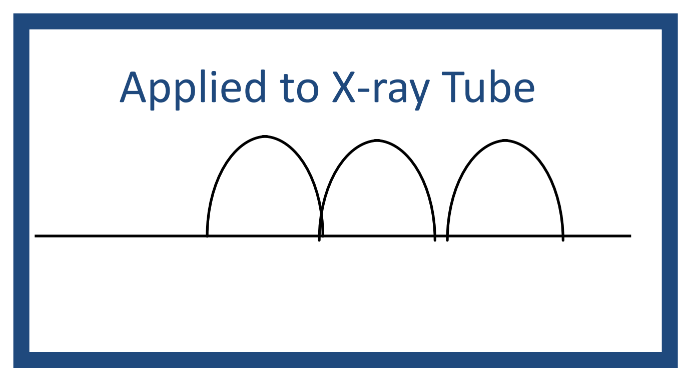
Voltage applied to tube



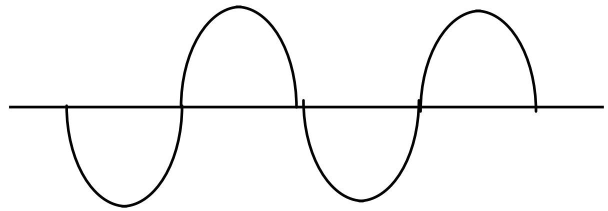
Self rectified waveform

Single phase Fullwave Rectifier

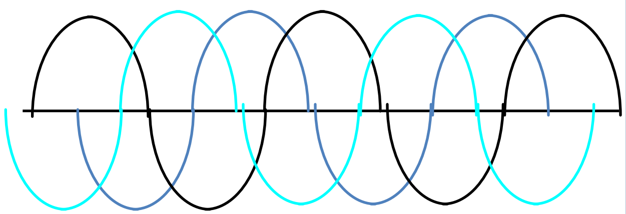




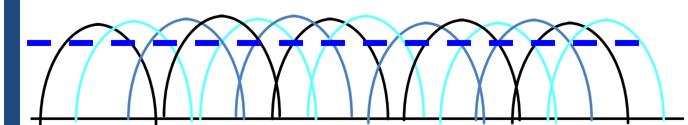
Three-Phase Generators



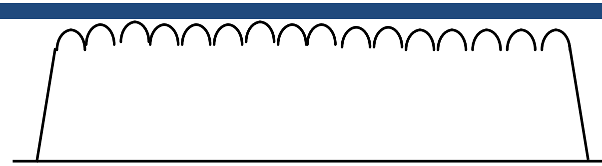
Single Phase Power



Input 3 Phase Voltage



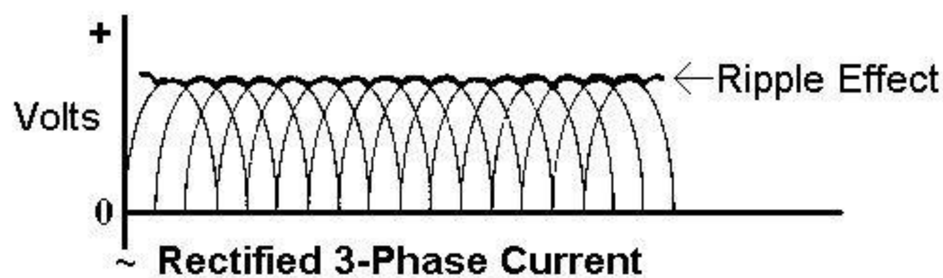
Rectified



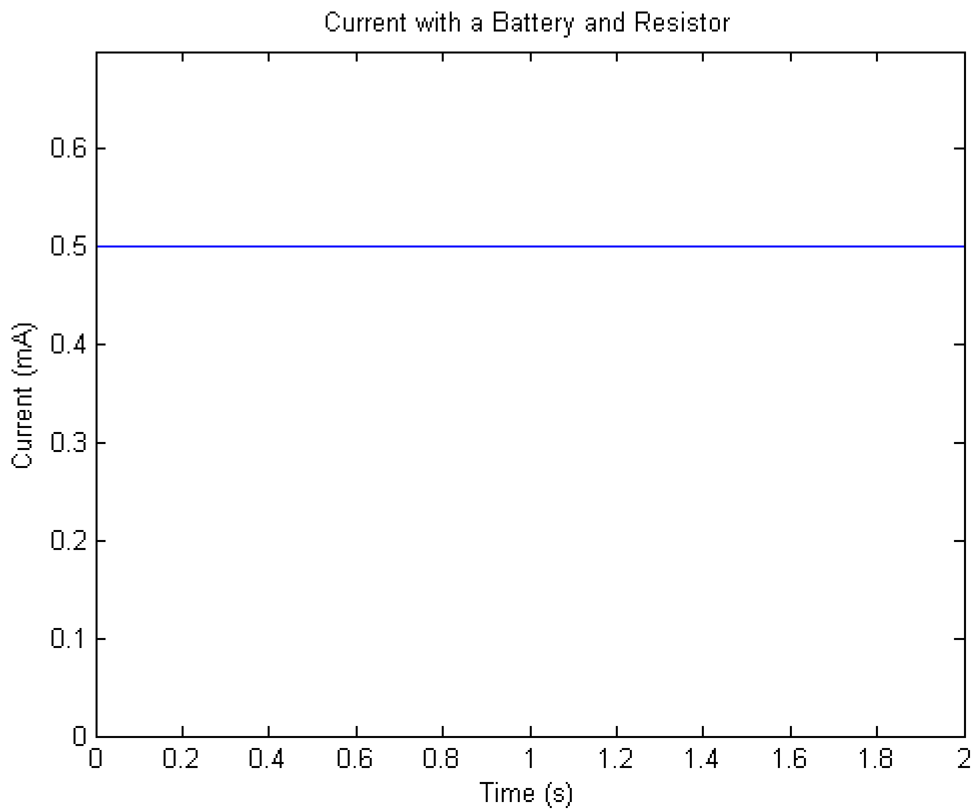
To X-Ray Tube

Three-Phase Generators

- 6-Pulse Twelve Rectifier
  - 13.5% ripple
- 12-Pulse Twelve Rectifier
  - 3.5% ripple
- Ripple = variation of kilovoltage from maximum



High frequency generators



Processes occurring in the target of x-ray tube

- Each electron arrives the surface of the target with a kinetic energy equivalent to the tube Kv (expressed in KeV)
- The electrons lose their energy by:

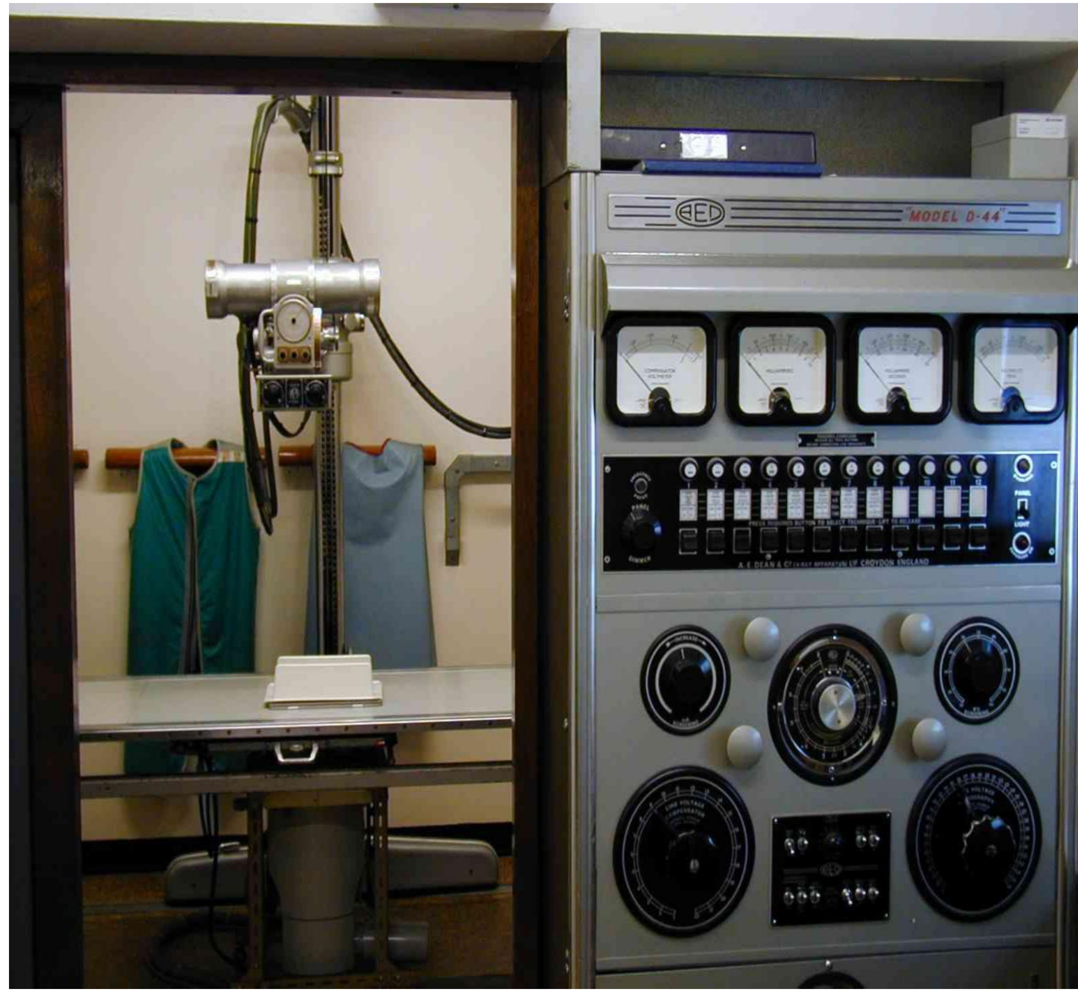
1) Interaction with outer electrons of the target → unwanted heat
2) X-ray production

X-Ray Production

- X-Rays are produced in the x-ray tube by two distinct processes
  - **Characteristic radiation**

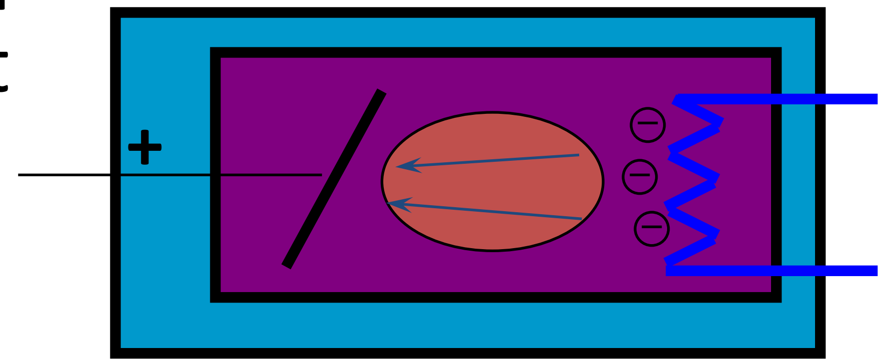
    0-28% of total x-ray beam energy
  - **Bremsstrahlung**

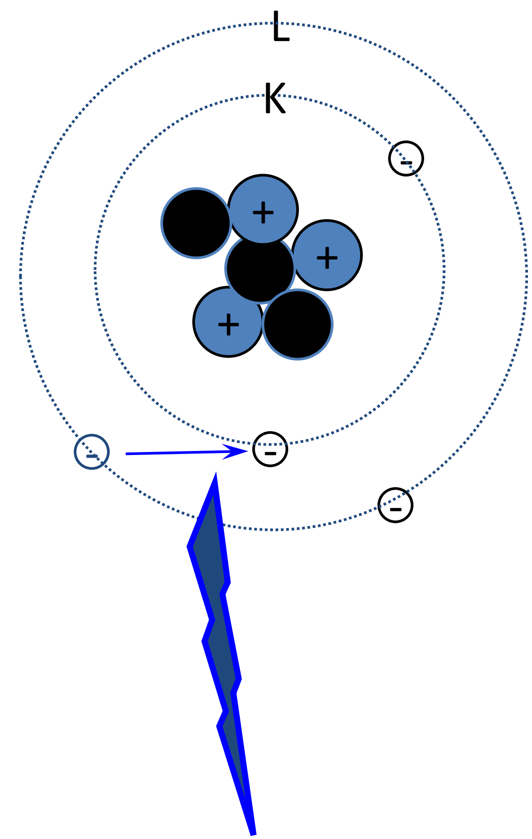
    The rest of X-ray beam



Characteristic Radiation

- High speed electron from cathode slams into target knocking out inner shell orbital electron
- orbital electron removed from atom
- electrons from higher energy shells cascade down to fill vacancies
- Characteristic x-rays emitted (Energy difference between shells emitted as characteristic x-ray)





Characteristic Radiation

- Probabilities:

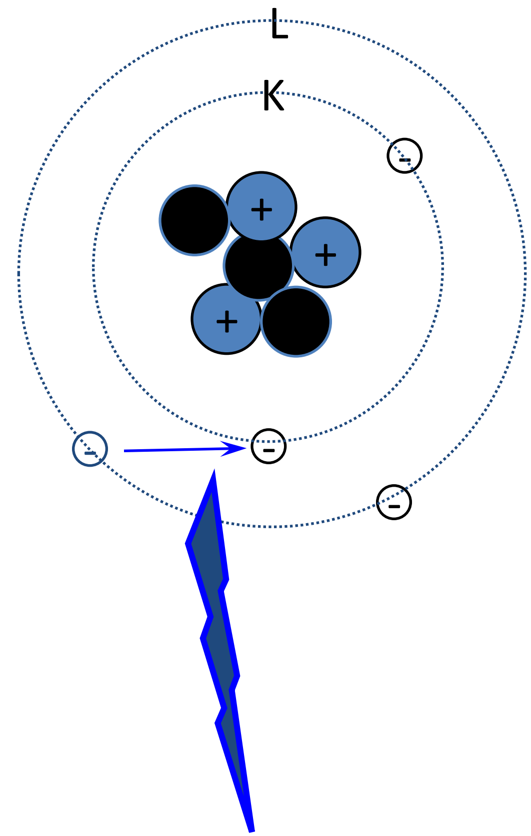
1) Electron from filament hit K shell electron of the target:

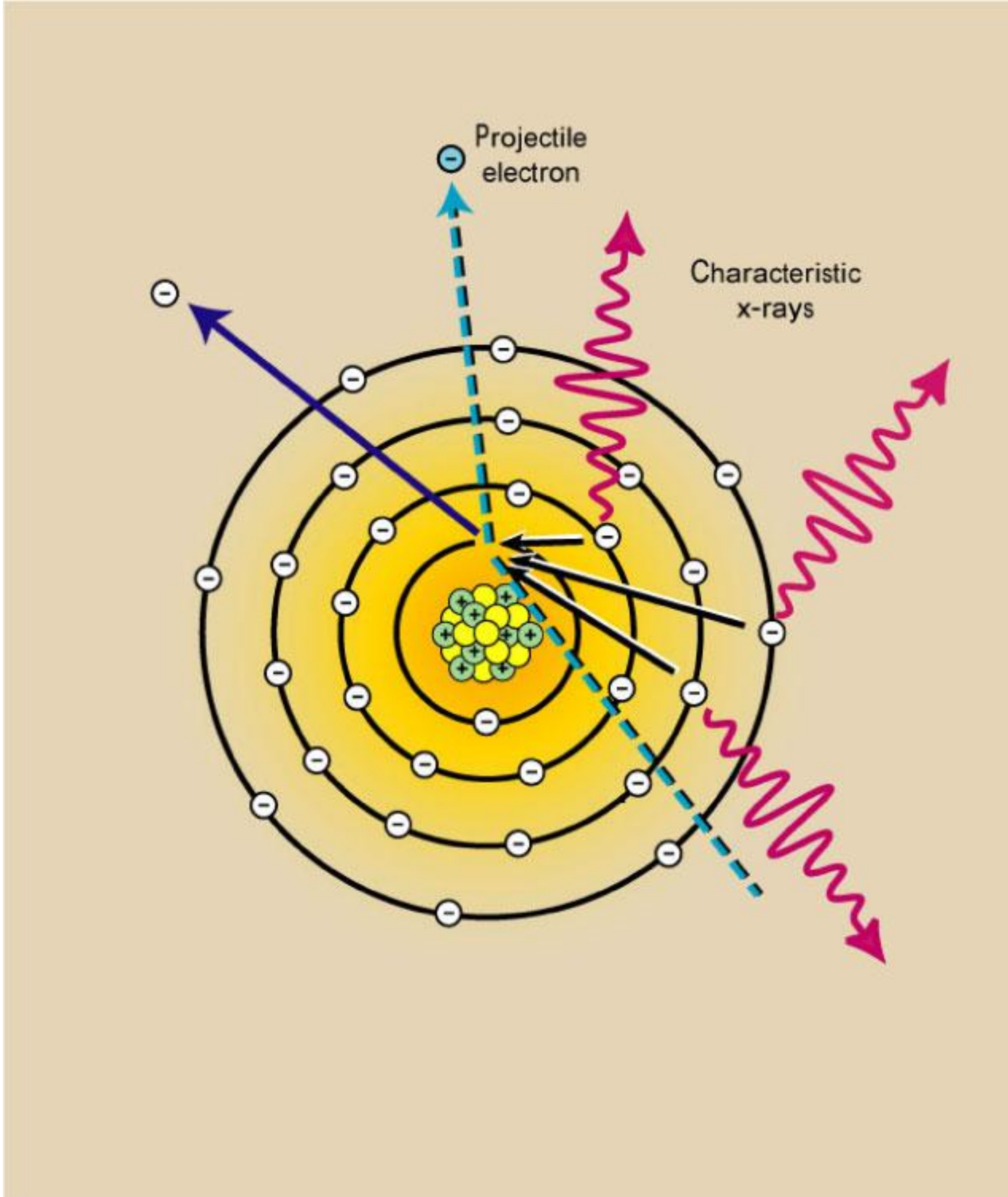
If L shell electron fill the vacancy in K shell : $K_\alpha = E_{k} - E_{L}$

If M shell electron fill the vacancy in K shell (less likely) : $K_\beta = E_{k} - E_{M}$

2)Electron from filament hit L shell electron of the target:

M shell electron fill the vacancy in L shell : L-radiation $= E_{L} - E_{M}$

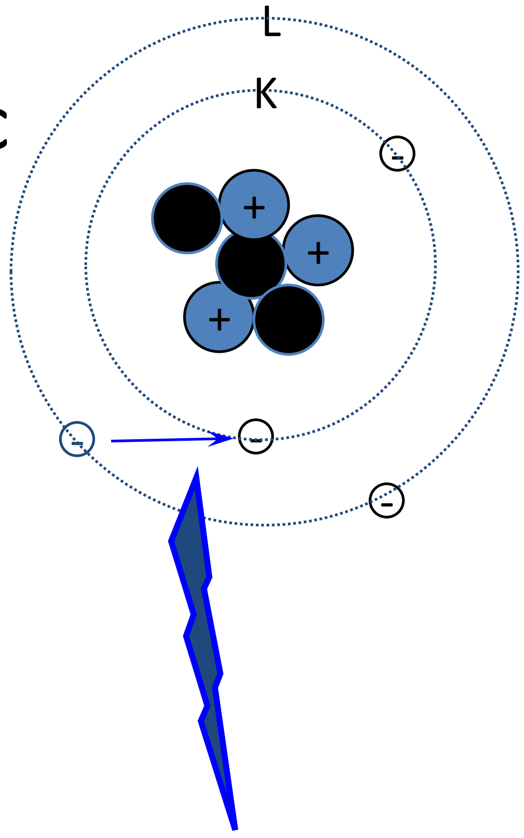



Projectile
electron
Characteristic
x-rays

Characteristic Radiation

- Consists only of discrete x-ray energies corresponding to energy difference between electron shells of target

(Specific energies are characteristic of target material)



Linear =Discrete spectrum

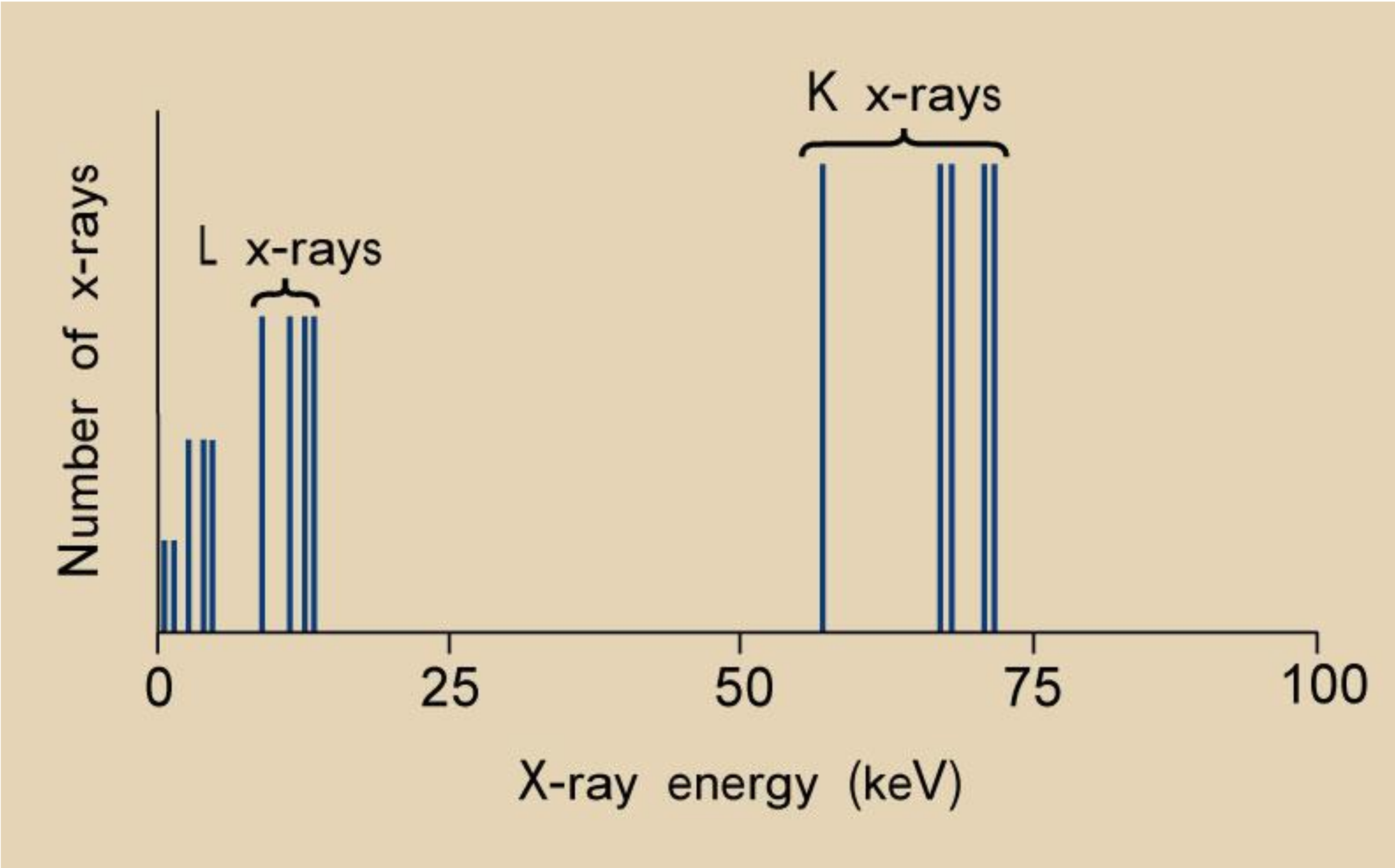
- Contains only specific values

- for tungsten: EK = 70 keV,
  EL = 12 keV , EM = 2 keV

→ K_α = 58 keV
  K_β = 68 keV
  L-radiation = 10 keV (does not leave X-RAY tube)

- For molybdenum :
  EK = 20 keV,
  EL = 2.5 keV

→ K_α = 17.5 keV
  K_β = 20 keV


K x-rays
L x-rays
Number of x-rays
0
25
50
75
100
X-ray energy (keV)

- Photon energy of characteristic radiation increase with

  ↑atomic number of the target

- Photon energy of characteristic radiation is unaffected by

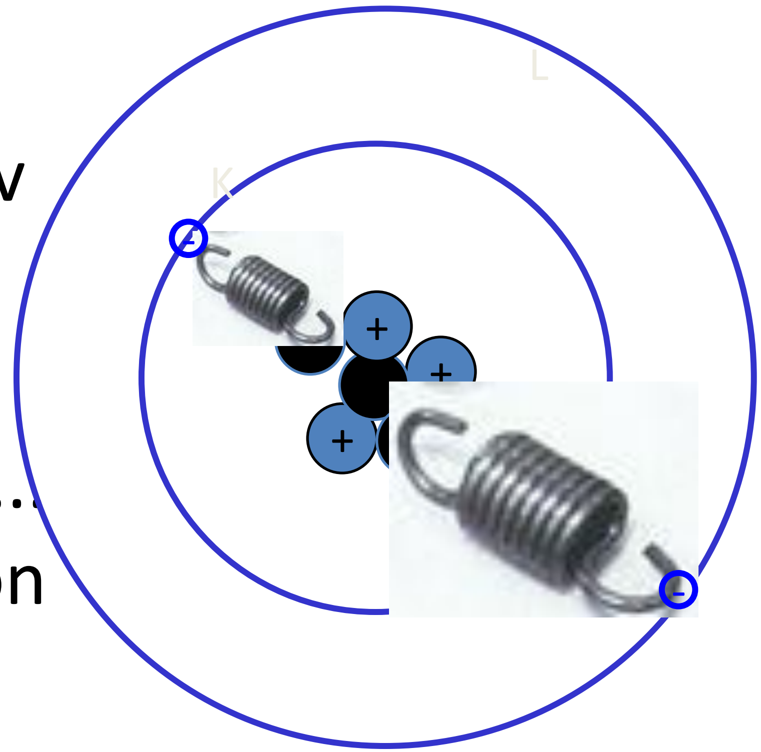
  tube voltage

- Rate of production of characteristic radiation is increased by

  ↑tube voltage

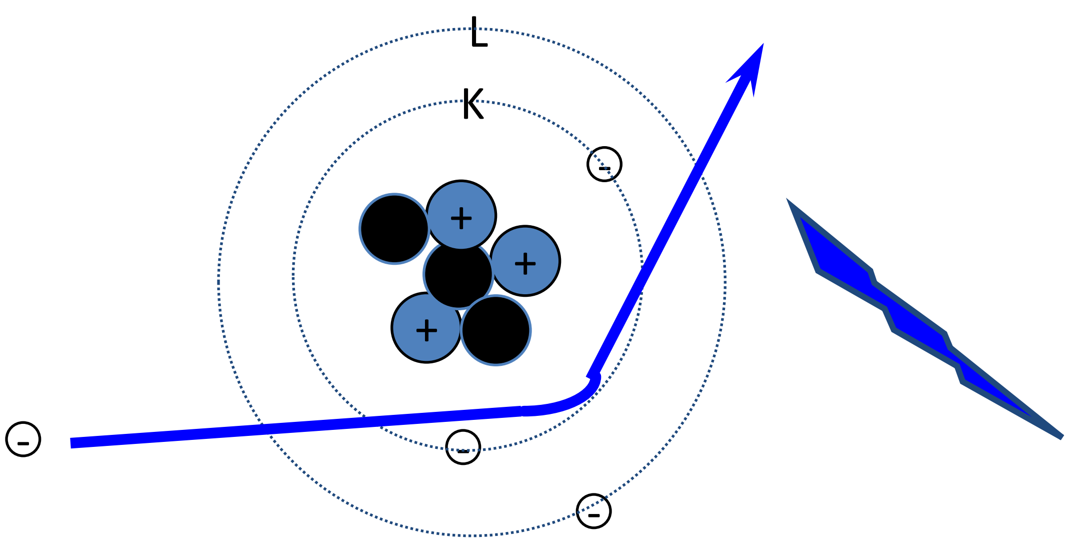
Characteristic Radiation (cont.)

- threshold energy required for incident electron (from cathode) to eject orbital electron = electron's binding energy
- For tungsten : Ek = 70 Kev
- If tube voltage , and so the maximum energy of electron is less than 70 ….. No characteristic radiation can be produced



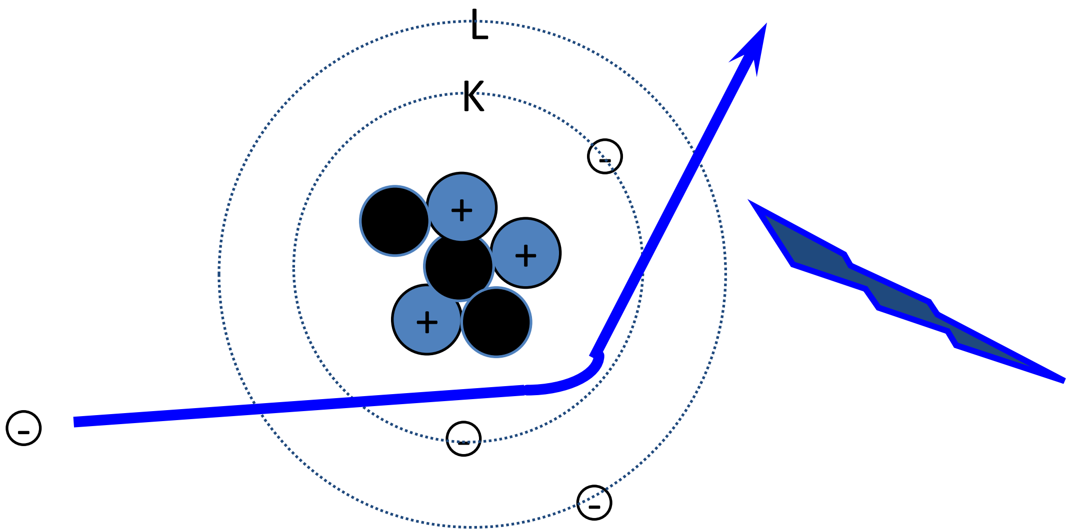
Bremsstrahlung

- interaction of moving electron with nucleus of target atoms
- Positive nucleus causes moving electron to change speed / direction
- Kinetic energy lost
- Emitted in form of Bremsstrahlung x-ray

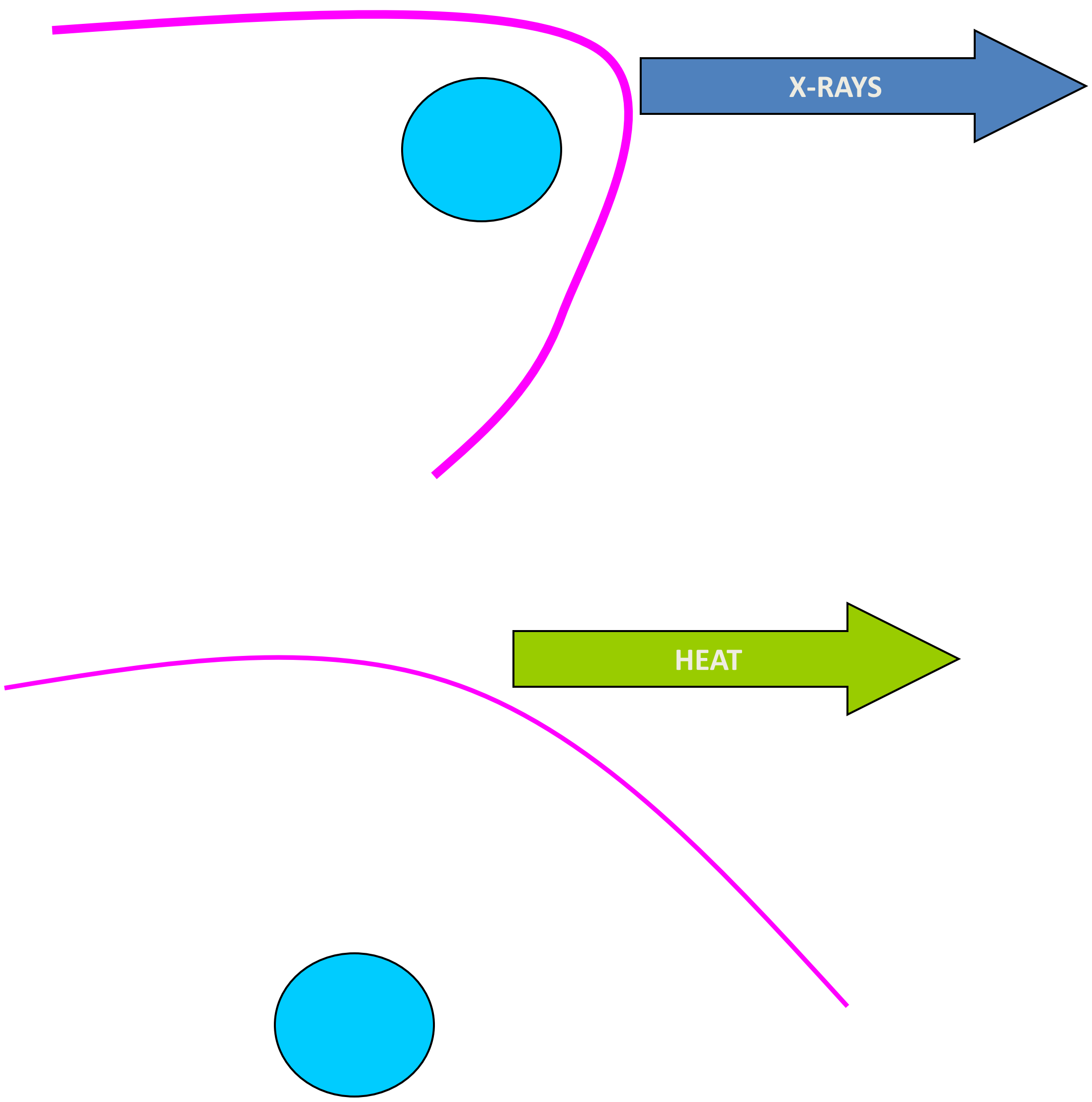


Bremsstrahlung (cont.)

- Bremsstrahlung means **braking radiation**
- Moving electrons have many Bremsstrahlung reactions
    - small amount of energy lost with each



DIFFERENT DEGREES OF DECCELERATION



Bremsstrahlung (cont.)

- Energy lost by moving electron is random & depends on
  - distance from nucleus
  - charge (Z) of nucleus
- Bremsstrahlung Energy Spectrum

  0 - peak kilovoltage (kVp) applied to x-ray tube

  - Largest photon energy that can be produced = tube kilovoltage (when electron is completely stopped)

  - most x-ray photons low energy

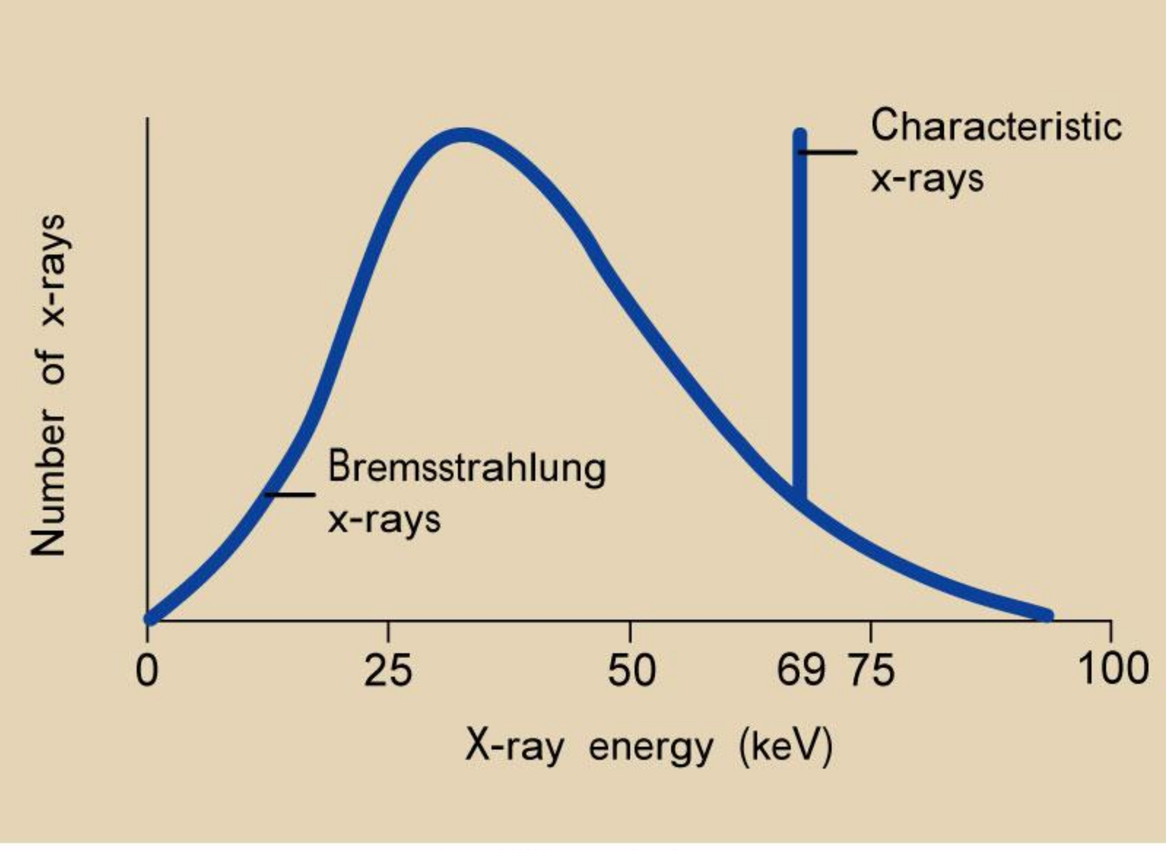
  - lowest energy photons don't escape tube
    (easily filtered by tube enclosures or added filtration)

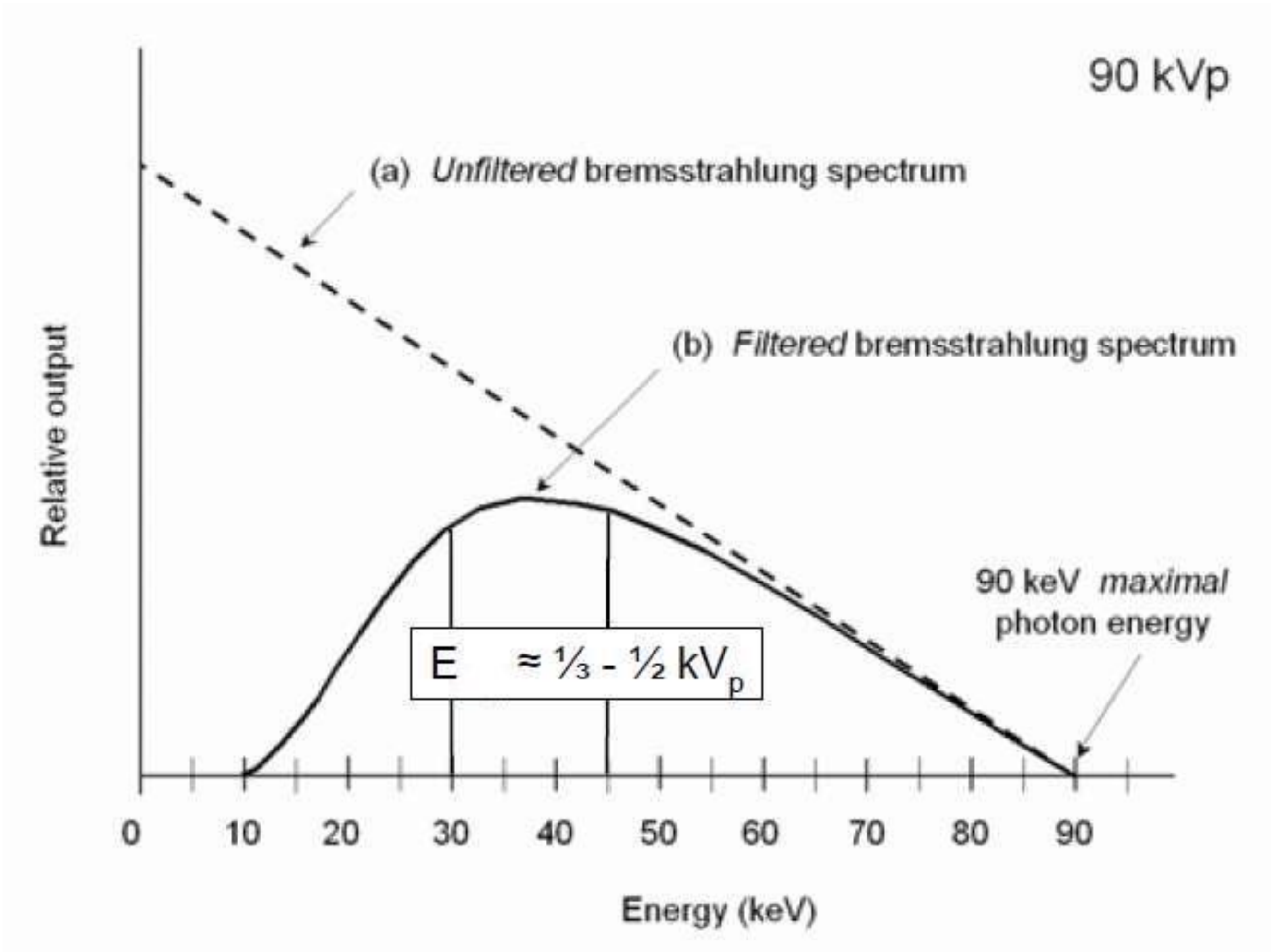
Bremsstrahlung is **POLYENERGETIC !**

- Except in mammography : 80% of x ray emitted are Bremsstrahlung

Bremsstrahlung X-ray Spectrum

- Brems x-rays have a range of energies and form a continuous emission spectrum



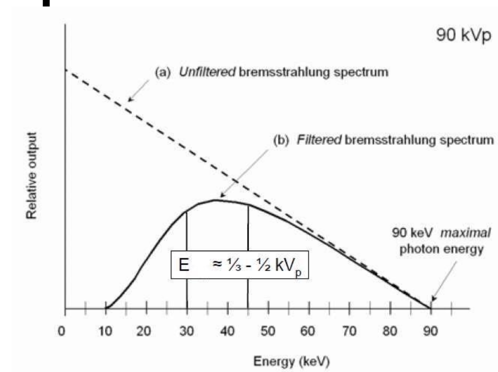


Dashed line = x ray produced near the target
Continues line = real x ray spectrum

Characteristics of x ray spectrum

- 1) low energy cut of at 10-20 keV : due to filtration (by glass wall , target itself…)

  the value of low energy cut off depends ONLY on filtration



- 2)maximum energy = Kv

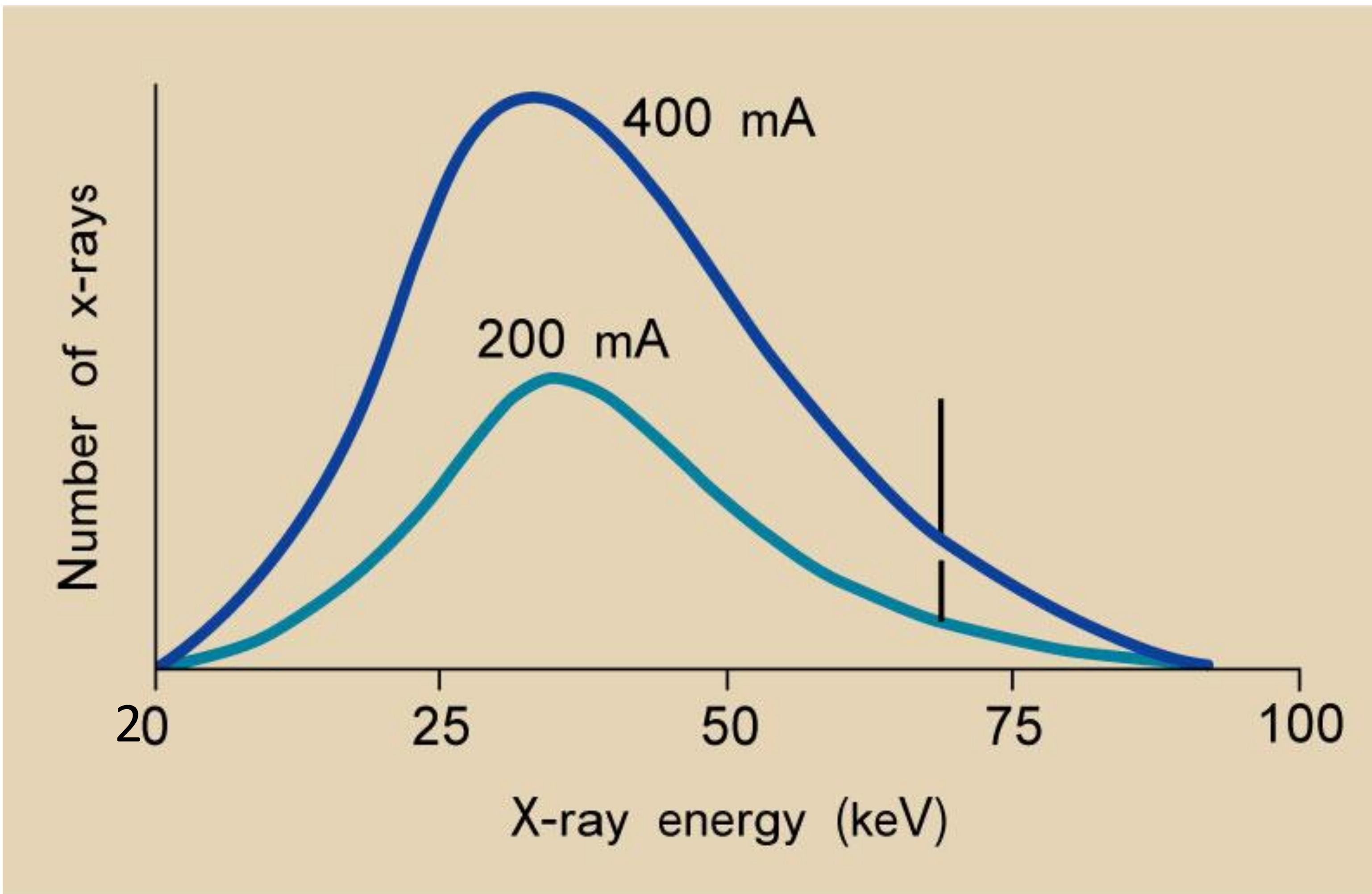
  (and depend ONLY on Kv)

- 3)peak of the spectrum (most common photon energy : between one third and one half of the Kv

- 4)average = effective energy = 50-60% of the maximum(X ray operating at 90 Kv : effectively emmiting 45 keV x ray) = x ray QUALITY

Factors affecting x ray spectrum

- 1) mA



mAs

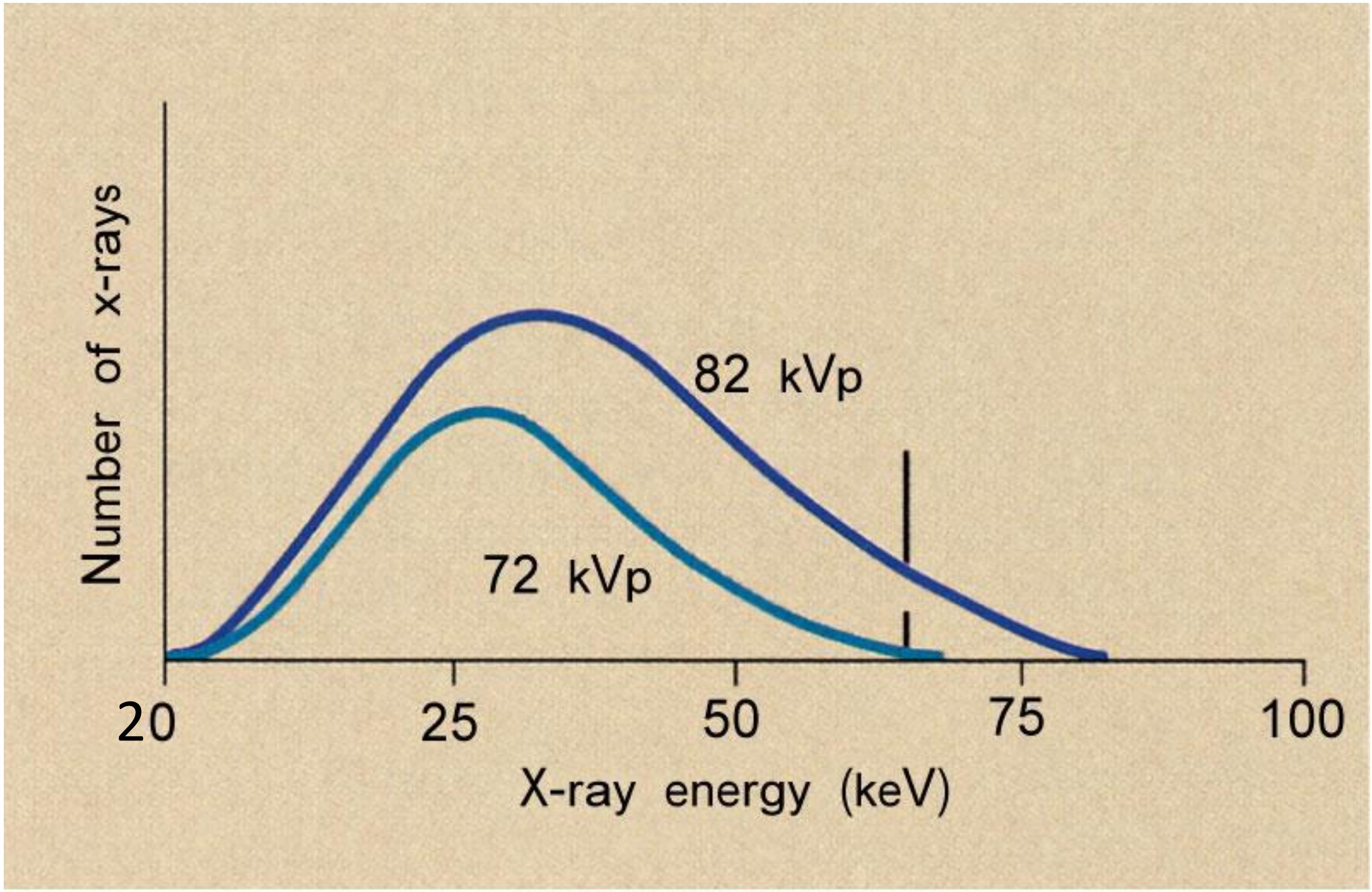
- Increase mA will increase x-ray output = **quantity** of both Bremsstrahlung and characteristic radiation
- Will NOT affect: maximum energy

  minimum energy

  effective energy

  shape of the spectrum

Effect of KV



KV

- Increasing Kv :
- 1)Increase: maximum energy

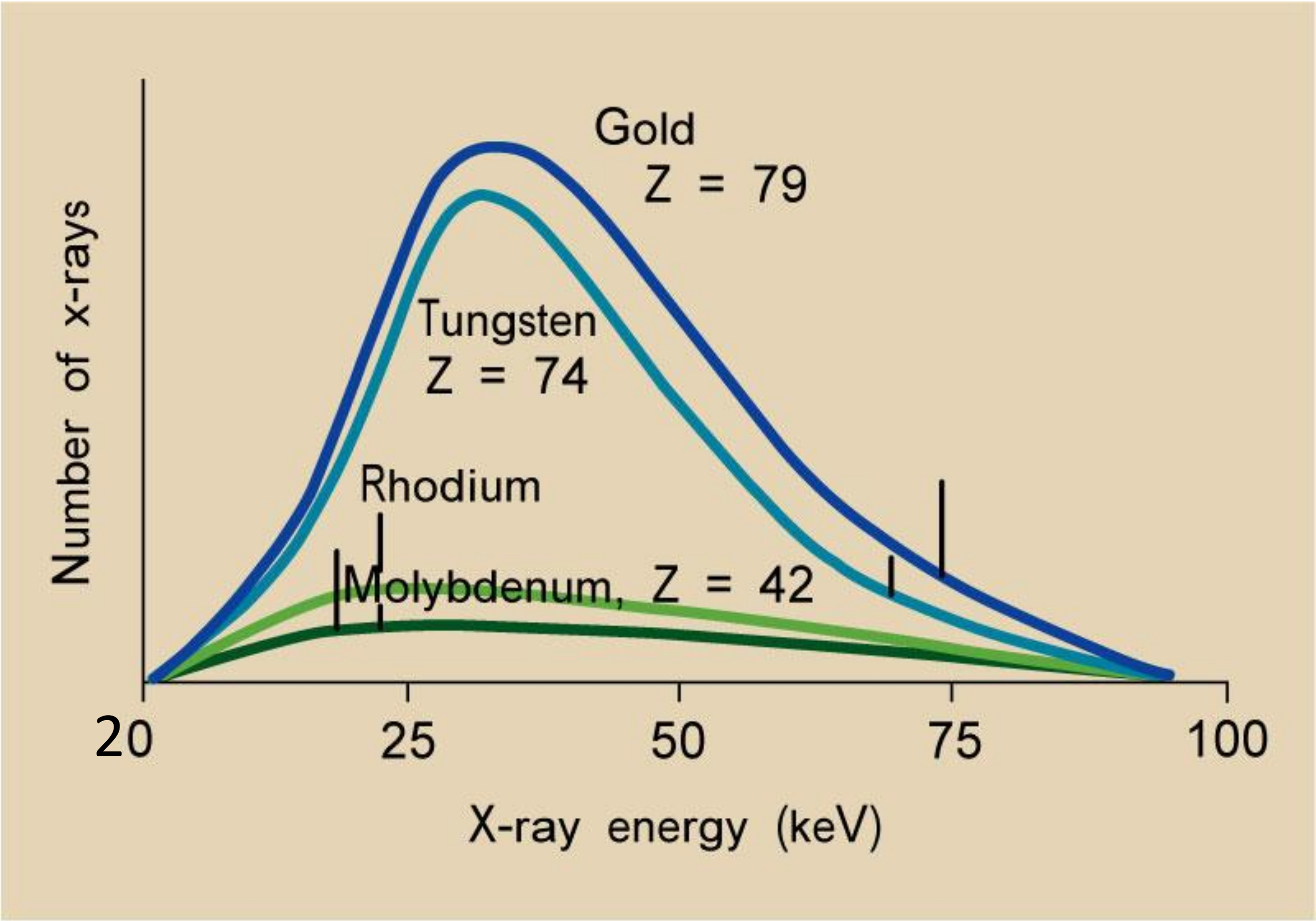
  effective energy

  X ray quantity (total number of photons)

i.e shifts the spectrum upwards and to the right

- Below certain kV: characteristic x-ray is not produced

Target material



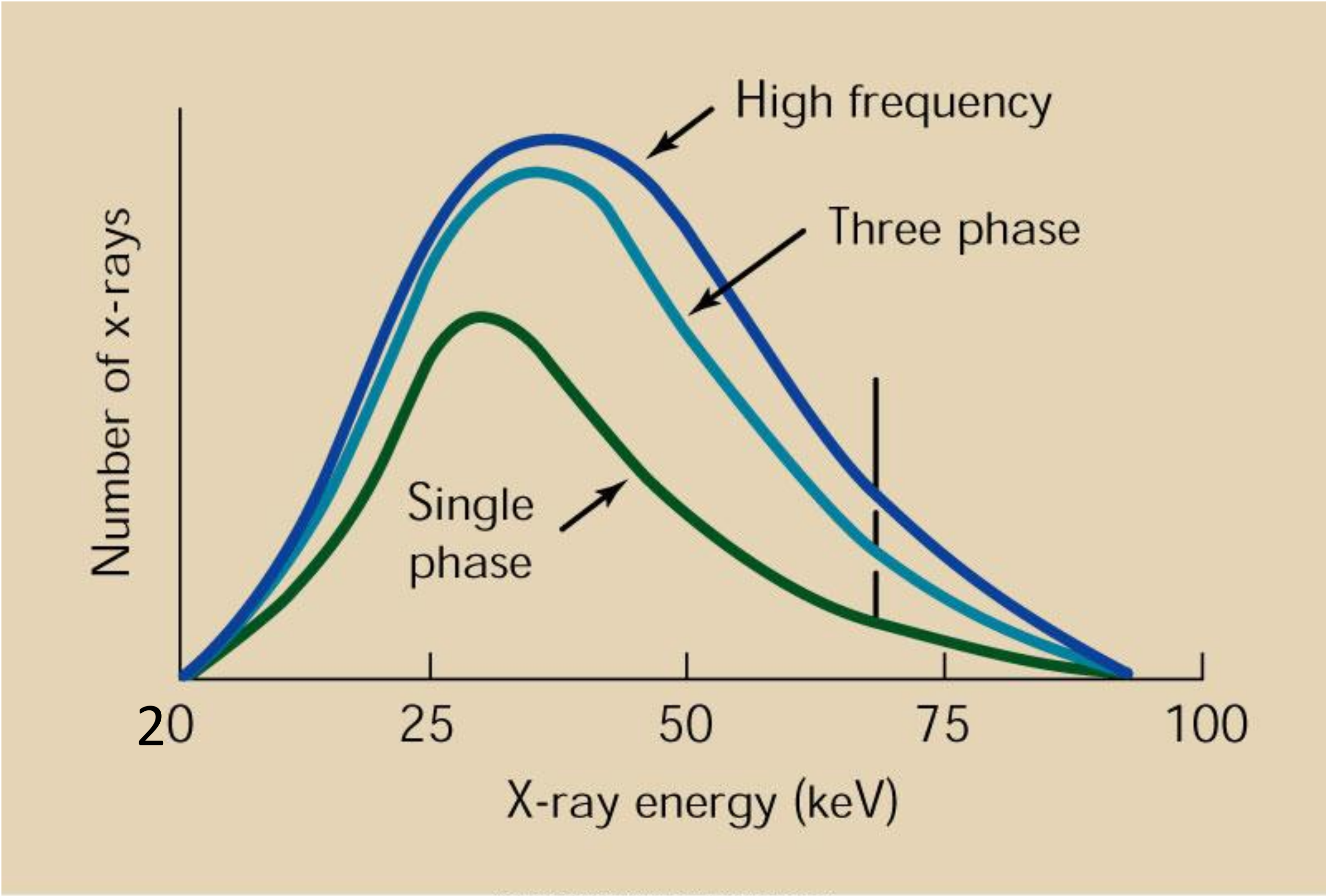
Target material

- Changing target material to one with higher atomic number:

1)increase x ray output (quantity= intensity)

2)increase ENERGY of characteristic radiation

KV waveform



High frequency
Three phase
Single phase
Number of x-rays
20
25
50
75
100
X-ray energy (keV)

KV waveform

- Maximum and minimum energies are unchanged
- Constant potential and 3 phase generators:

  produce more x ray at higher energies

  so that:

  1)↑x ray quantity = ↑ output = ↑ intensity

  2) ↑ effective energy of the beam (tube voltage at the same PEAK value throughout the exposure)

Factors affecting X-ray Intensity

- Milliampere-seconds (mAs) : x-ray quantity is proportional to mAs
- Distance : x-ray intensity varies inversely with the square of the distance from the x-ray target
- Kilovolt Peak (kVp) : x-ray quantity is proportional to kVp^2

i.e. If kVp were doubled the x-ray intensity would increase by a factor of four or kVp^2

Efficiency of x ray production

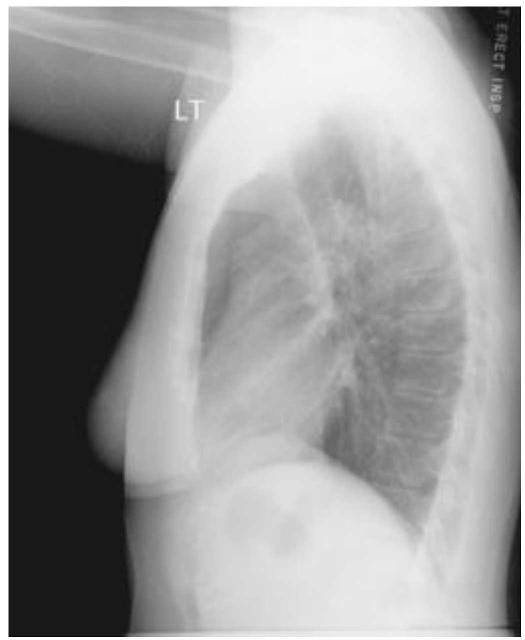
- = x ray output / electrical power supplied
- X ray output α kVp^2 x mAs
- Electrical power supplied α kVp x mAs
- So that Efficiency of x ray production increase with

1)Kvp

2)Z of target material

3) Kv waveform

X ray attenuation

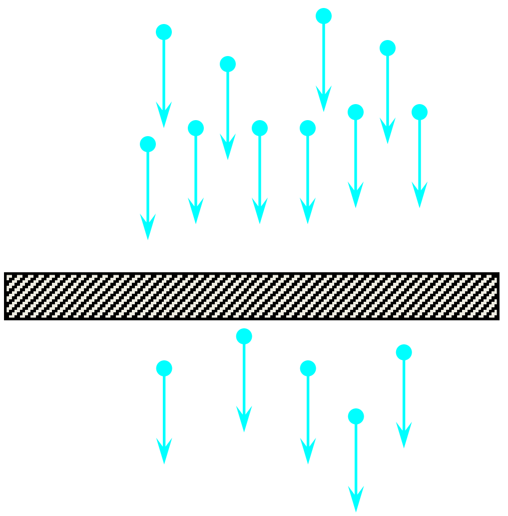


X ray attenuation

- Reduction of number of photons of a beam after emerging through a material

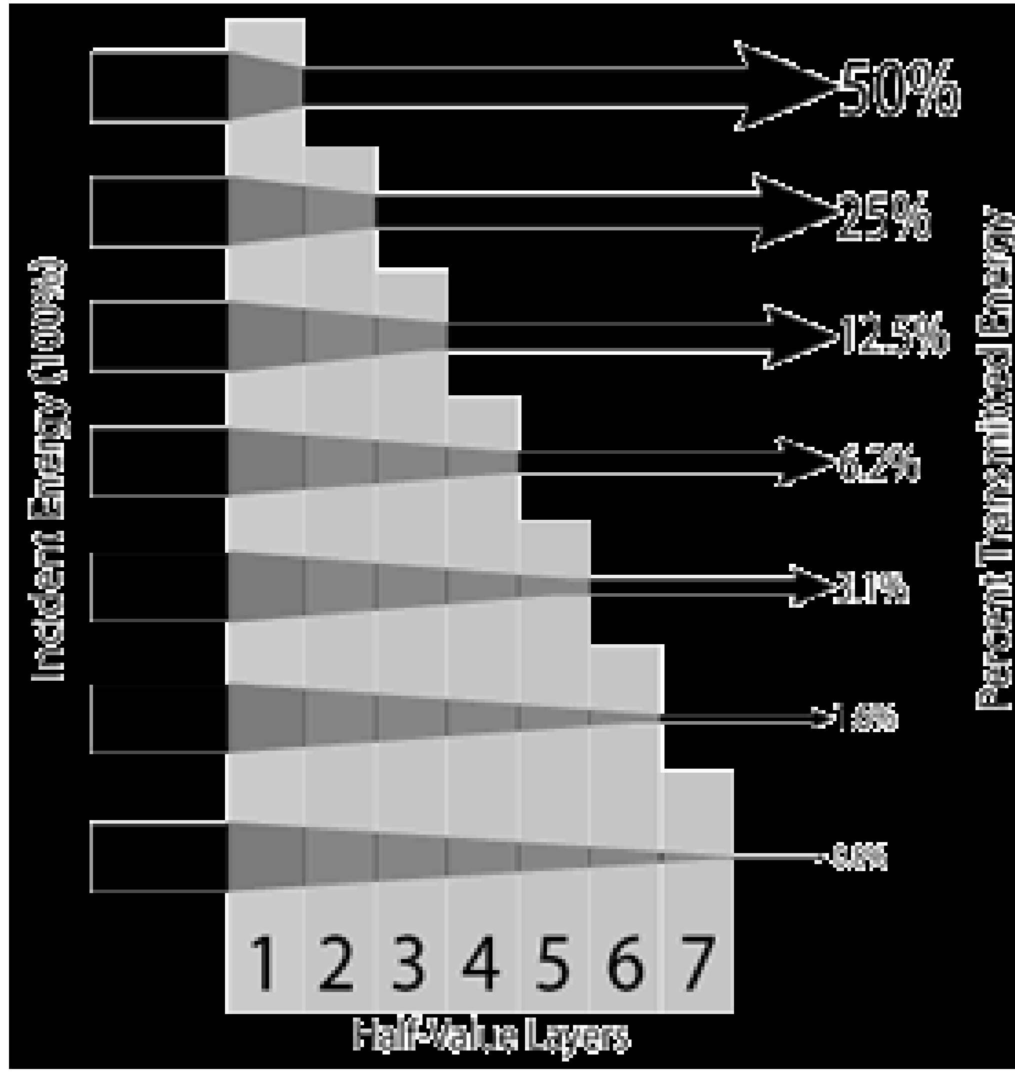
Monochromatic Radiation

- Radioisotope
  - Not x-ray beam
- all photons in beam have <u>same energy</u>
- Equal thickness of absorber transmit equal fractions of radiation
- attenuation results in
  - Change in beam quantity
  - <u>no change</u> in beam quality
    - # of photons & total energy of beam changes by same fraction



Half value layer HVL

- Thickness of the stated material that would reduce the intensity of the beam to half of its original value
- Two HVL reduce the intensity by factor of $2^2 = 4$
- Ten HVL reduce the intensity by factor of $2^{10} = 1024$



Linear Attenuation Coef.

-Inversely proportional to HVL

-Linear attenuation coefficient (μ)= 0.693/HVL

- Units:
  1 / cm

Larger Coefficient = More Attenuation

Applies only to Monochromatic radiation beam

Factors affecting HVL and Linear attenuation coefficient

- 1)↑density of the material → ↑μ &↓ HVL
- 2)↑atomic number of the material → ↑μ &↓ HVL
- 3) ↑photon energy of radiation → ↓μ &↑ HVL

Note that HVL is:

1) Indication of beam quality

2) Valid concept for all beam types

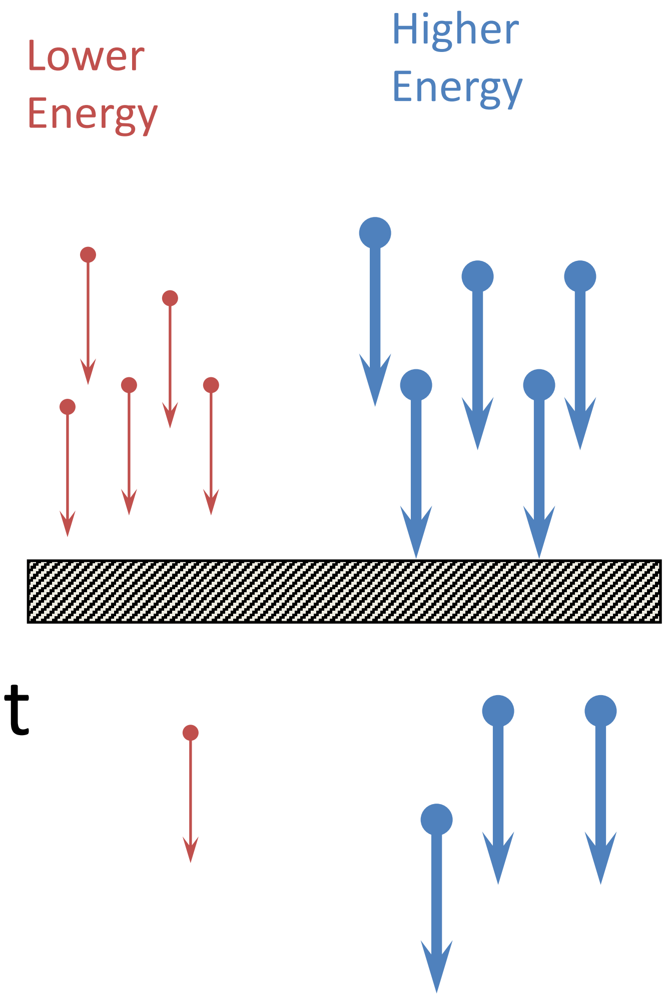
Mono-energetic

Poly-energetic

3) Higher HVL means

more penetrating beam

lower attenuation coefficient



Mass Attenuation Coef.

- *Mass* attenuation coefficient = linear attenuation coefficient divided by density
  - Independent on density
  - expresses attenuation of a material **independent of physical state**
  - **Only dependant on Z and photon energy**
  - Unit = **cm ^{2} / g**

Exponential graph

- Formula

$$I = I_o e^{-\mu d}$$

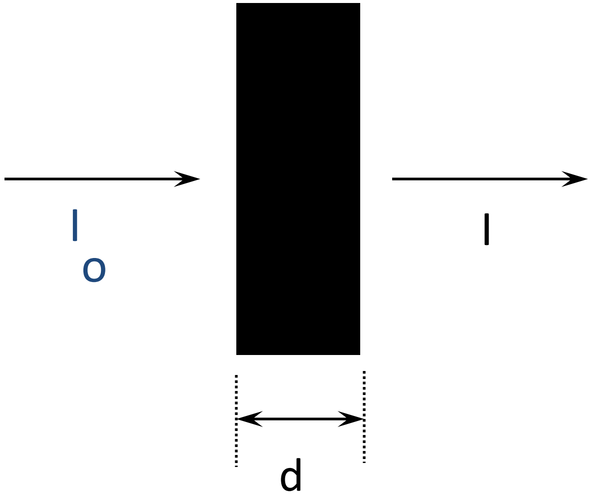
I_o = Intensity of incident radiation

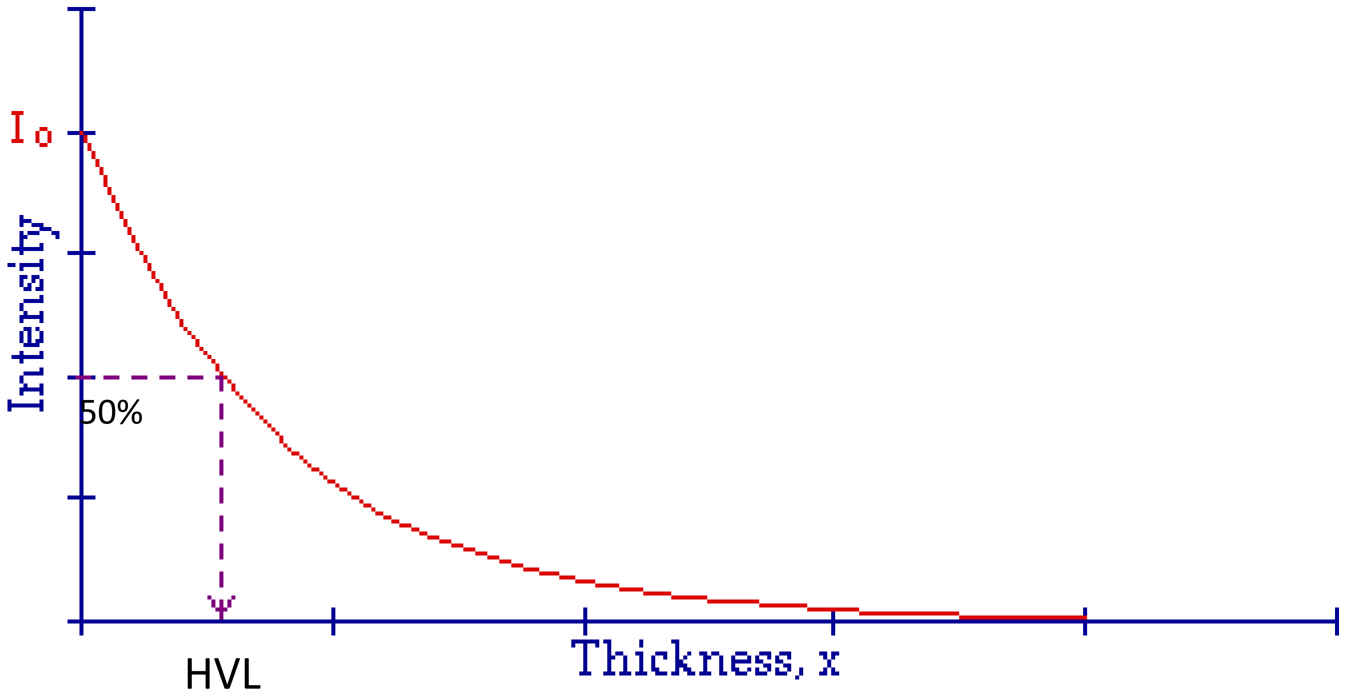
I = Intensity of transmitted radiation

e = base of natural logarithm

μ = linear attenuation coefficient

d = absorber thickness (cm)

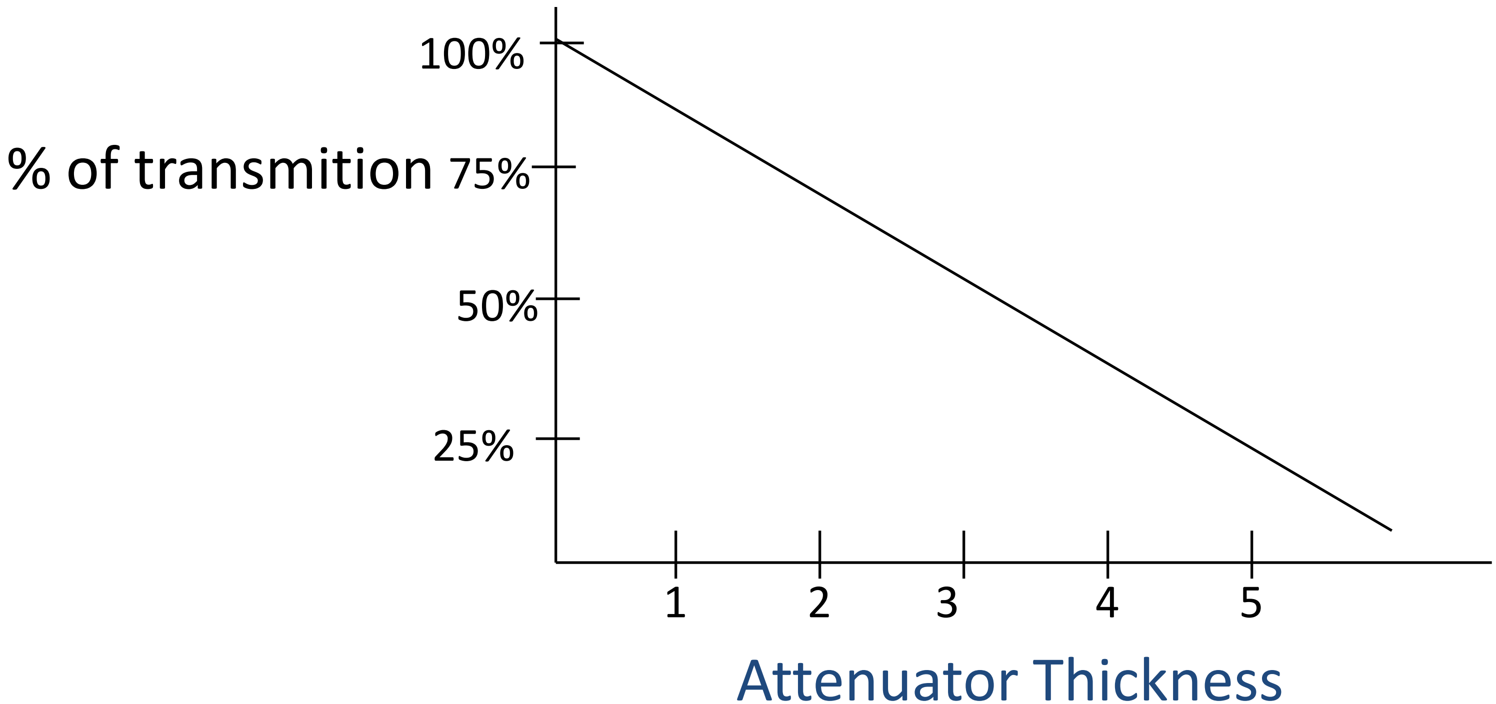




Linear scale →exponential curve

Note that beam intensity never reaches zero

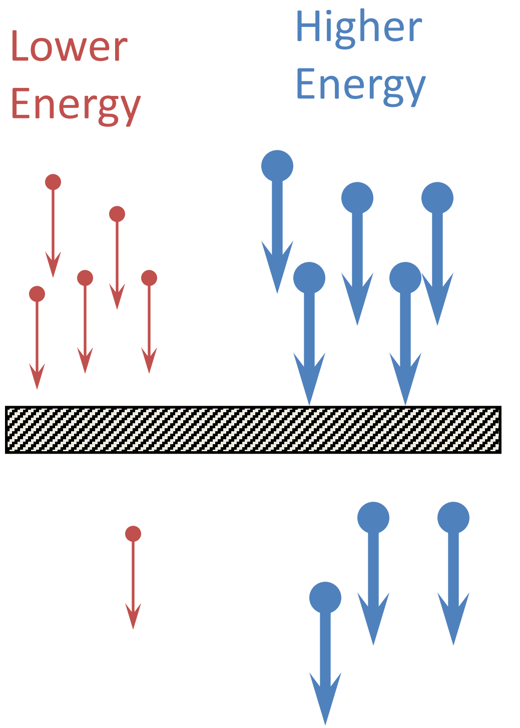
Logarithmic scale →linear curve



Attenuation of Polychromatic Radiation

- X-Ray beam contains spectrum of photon energies (remember?)

- Lower energy photons are attenuated more than higher energy photons



Results:

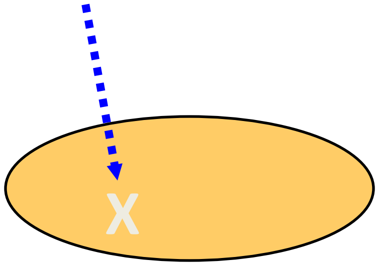
- Attenuation alters beam quantity
- Attenuation alters beam QUALITY :
    - **Higher fraction of low energy photons removed**
    - **Beam Hardening occur = proportion of high energy photons increase**
    - **As beam penetrates the material , it becomes progressively more HOMOGENOUS**
    - **Average energy increase → second HVL (which reduce intensity from 50% to 25%) will be GREATER than first HVL**
    - **HVL can be calculated for poly-energetic beams by using effective beam energy**

Basic Interactions Between X-Rays and Matter

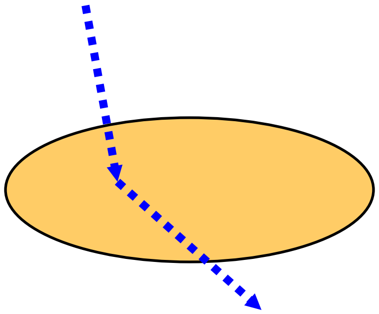
Photon Phate

*

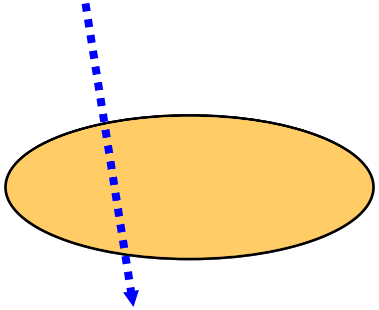
- **absorbed**
  - completely removed from beam
  - ceases to exist



- **scattered**
  - change in direction
  - no useful information carried
  - source of noise



- Nothing
  - Photon passes unmolested

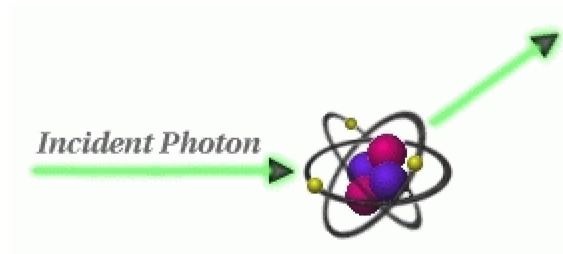


Basic Interactions

- Coherent Scattering
- Pair Production
- **Photoelectric Effect**
- **Compton Scattering**

Coherent Scattering

- Also called
  - unmodified scattering
  - classical scattering



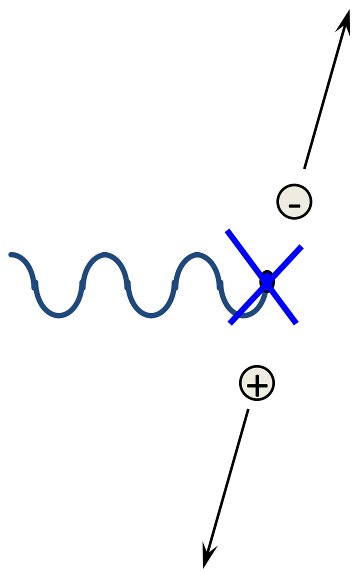
- Photon energy is less than electron binding energy
- Change in direction
- No change in energy
- <u>No</u> ionization
- Contributes to scatter as film fog
- Less than 5% of interactions
- Increase probability with decrease of photon energy

Pair Production Process

- high energy photon interacts with nucleus
- photon disappears
- **electron** & **positron** (positive electron) created
- energy in excess of 1.02 MeV given to electron/positron pair as kinetic energy.
- Positron undergoes

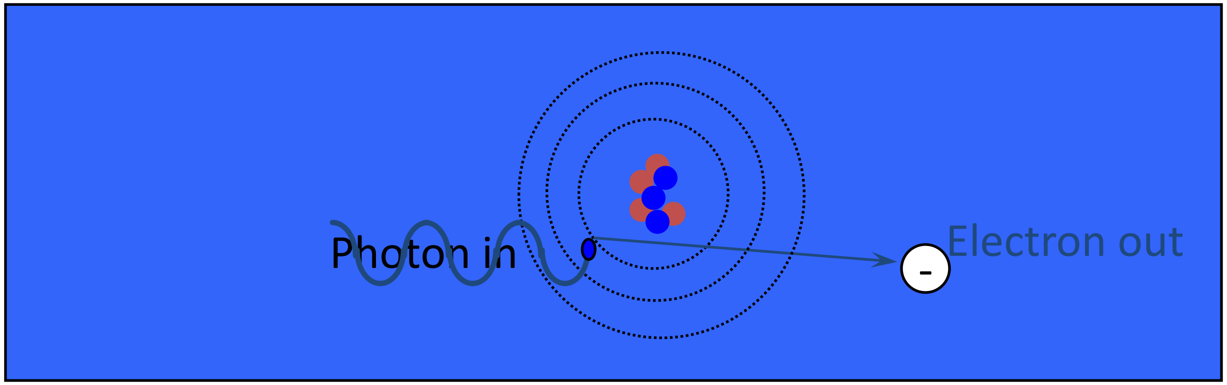
ANNIHILATION REACTION

SEE PET

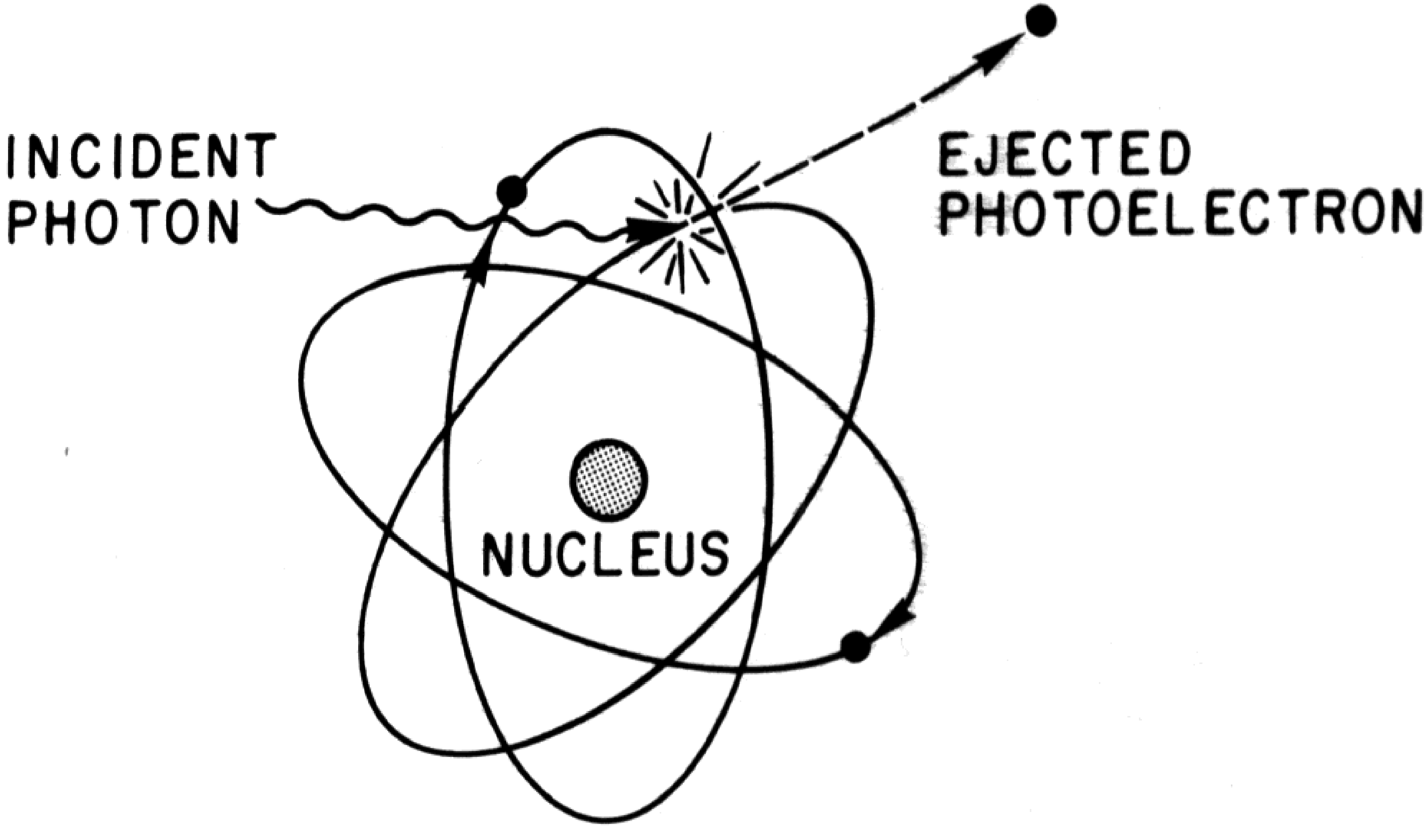


Photoelectric Effect

- photon interacts with bound (inner-shell) electron
- electron liberated from atom (ionization)
- photon disappears



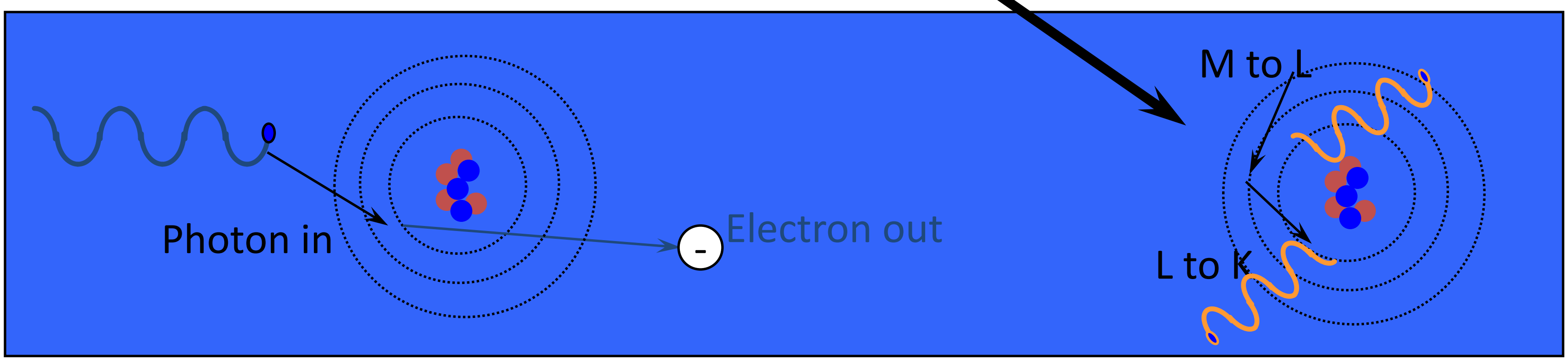
PHOTOELECTRIC EFFECT



Photoelectric Effect

- Exiting electron kinetic energy

  = incident energy - electron's binding energy
- electrons in higher energy shells cascade down to fill energy void of inner shell
  - **characteristic radiation**



Photoelectric Interaction Probability

- inversely proportional to cube of photon energy
  - low energy event
- proportional to cube of atomic number
- proportional to the physical density (as all attenuation processes)
- more likely with inner (higher) shells
  - tightly bound electrons

$$\boxed{P.E. \sim \frac{1}{\text{energy}^3}}$$

$$\boxed{P.E. \sim Z^3}$$

Photoelectric Effect

- Interaction much more likely for
  - low energy photons
  - high atomic number elements

$$P.E. \sim \frac{1}{\text{energy}^3}$$

$$P.E. \sim Z^3$$

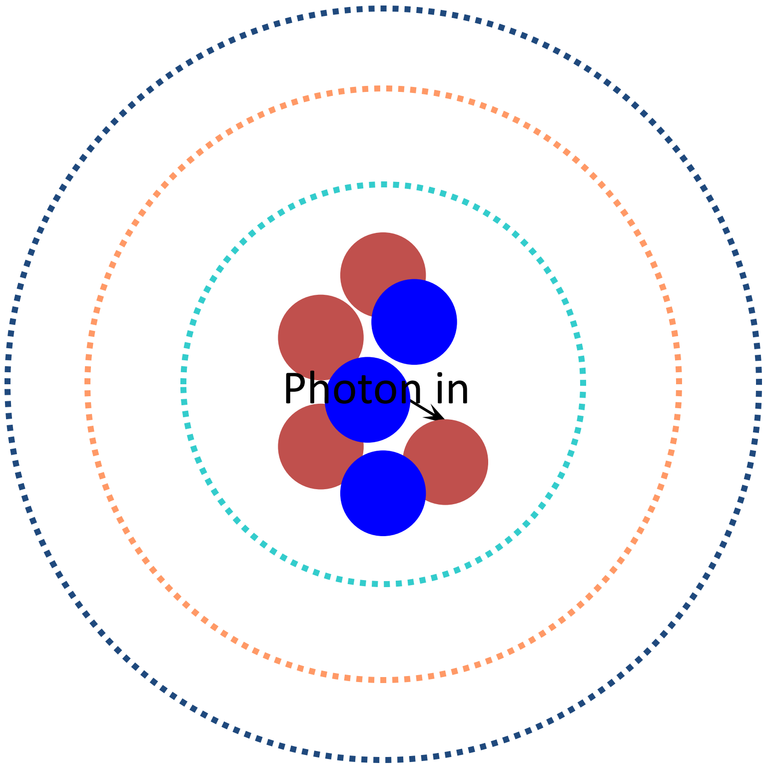
Photoelectric Effect

- Photon Energy Threshold to cause photoelectric effect
  - $\geq$ binding energy of orbital electron
- binding energy depends on
  - atomic number
    - higher for increasing atomic number
  - shell
    - lower for higher (outer) shells
- most likely to occur when photon energy & electron binding energy are nearly the same

Photoelectric Threshold

- Binding Energies
  - K: 100
  - L: 50
  - M: 20

Photon energy: 15

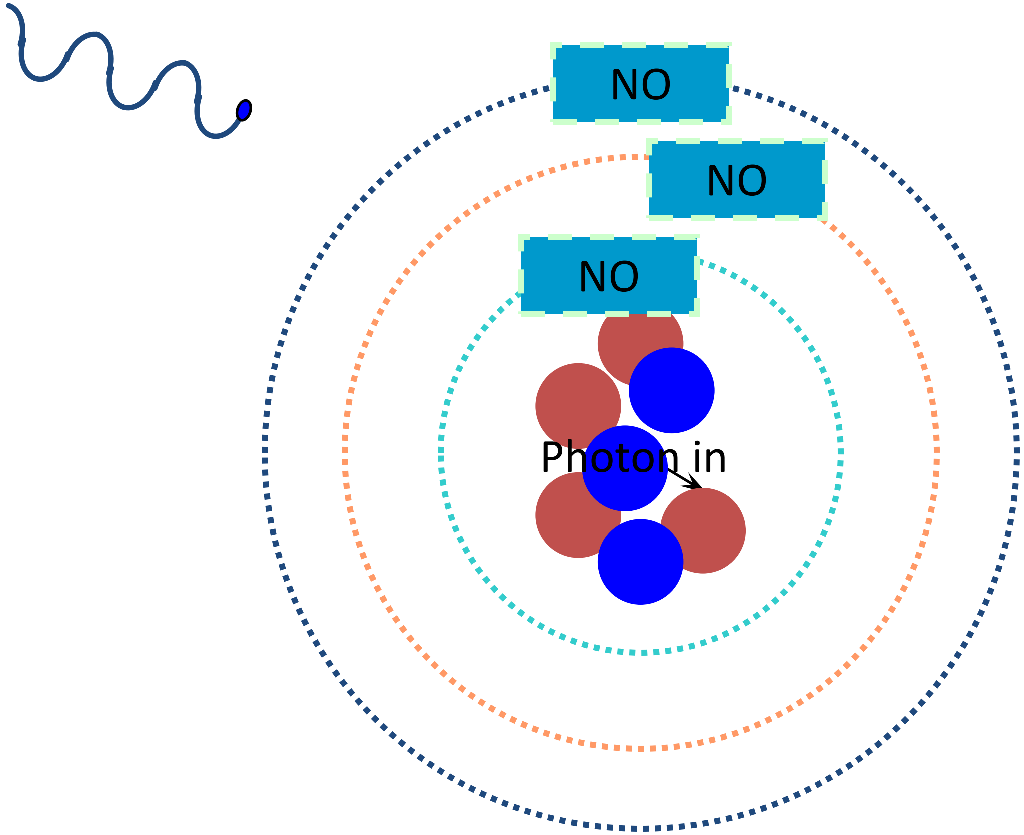


Which shells are candidates for photoelectric interactions?

Photoelectric Threshold

- Binding Energies
  - K: 100
  - L: 50
  - M: 20

Photon energy: <u>15</u>



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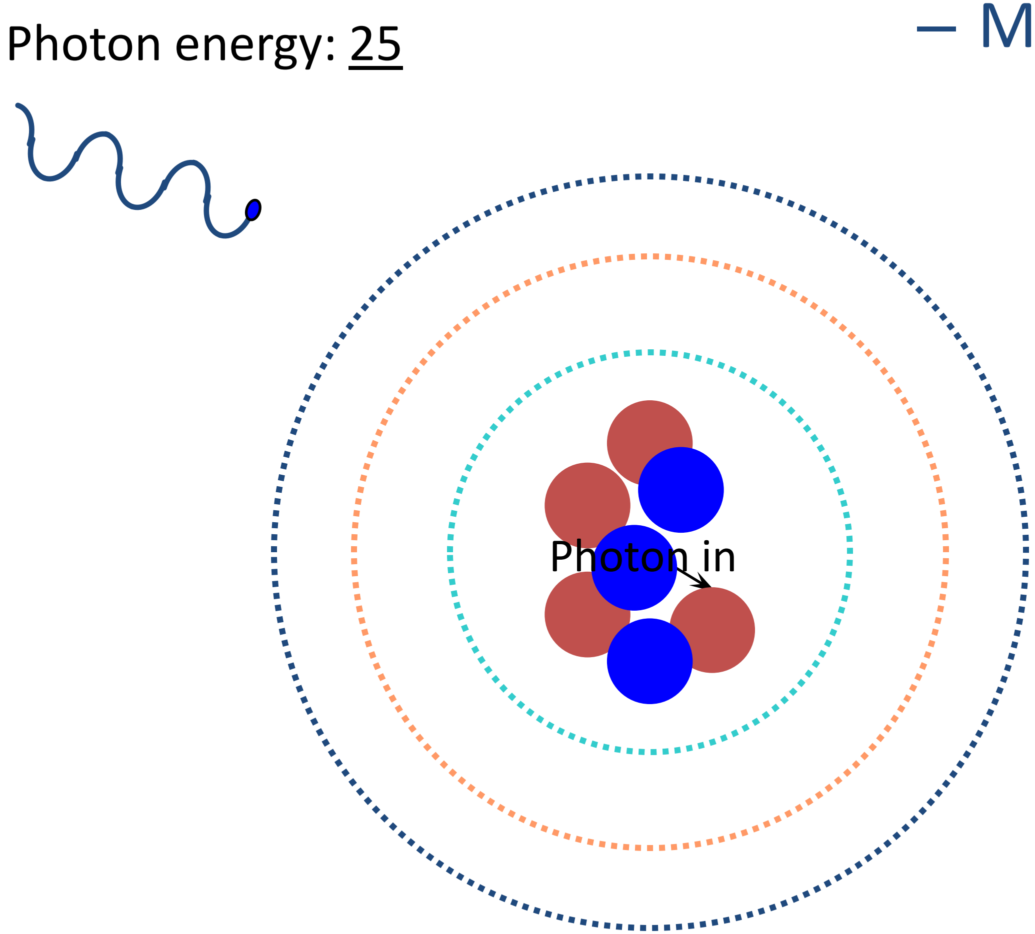
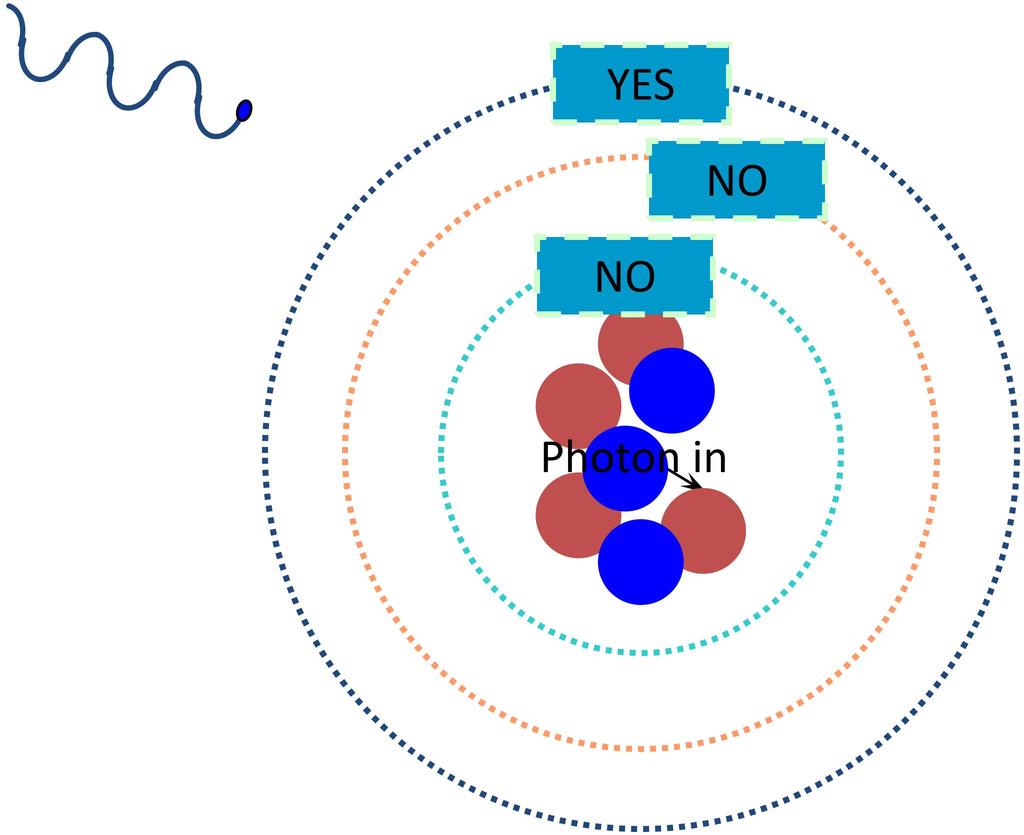


Which shells are candidates for photoelectric interactions?

Photoelectric Threshold

- Binding Energies
  - K: 100
  - L: 50
  - M: 20

Photon energy: 25

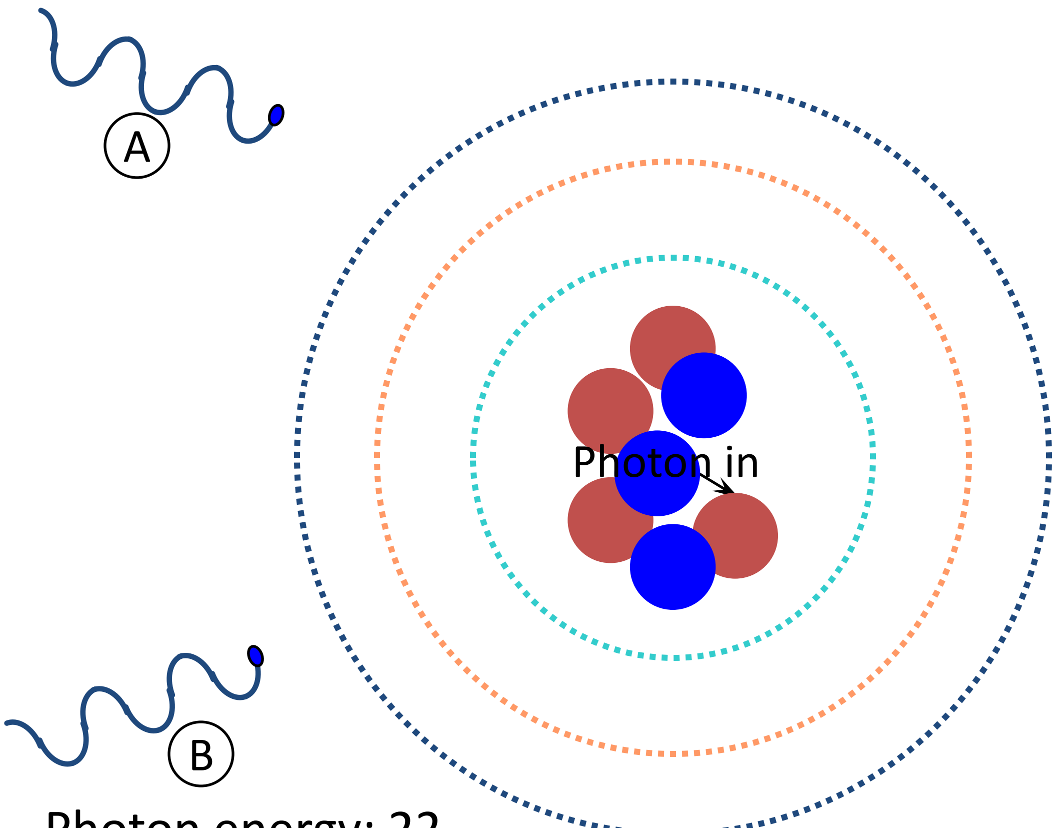


Which shells are candidates for photoelectric interactions?

Photoelectric Threshold

- Binding Energies
  - K: 100
  - L: 50
  - M: 20

Photon energy: 25



Photon energy: 22

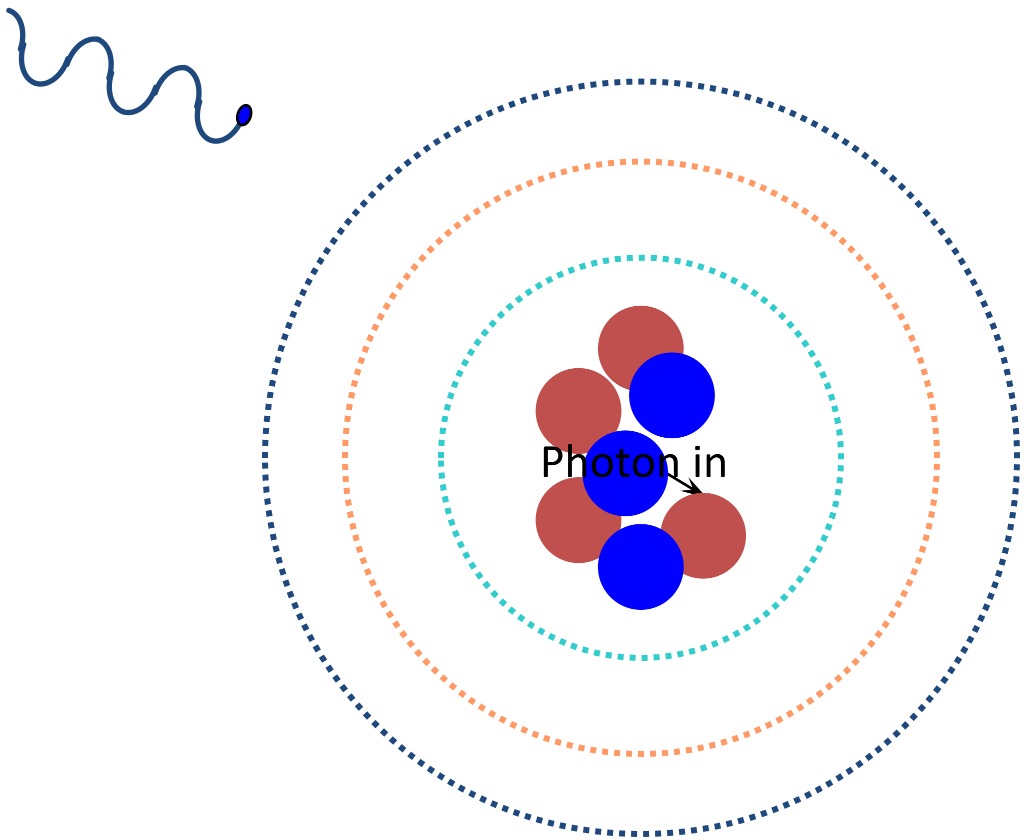
$$P.E. \sim \frac{1}{\text{energy}^3}$$

Which photon has a greater probability for photoelectric interactions with the m shell?

Photoelectric Threshold

- Binding Energies
  - K: 100
  - L: 50
  - M: 20

Photon energy: 55

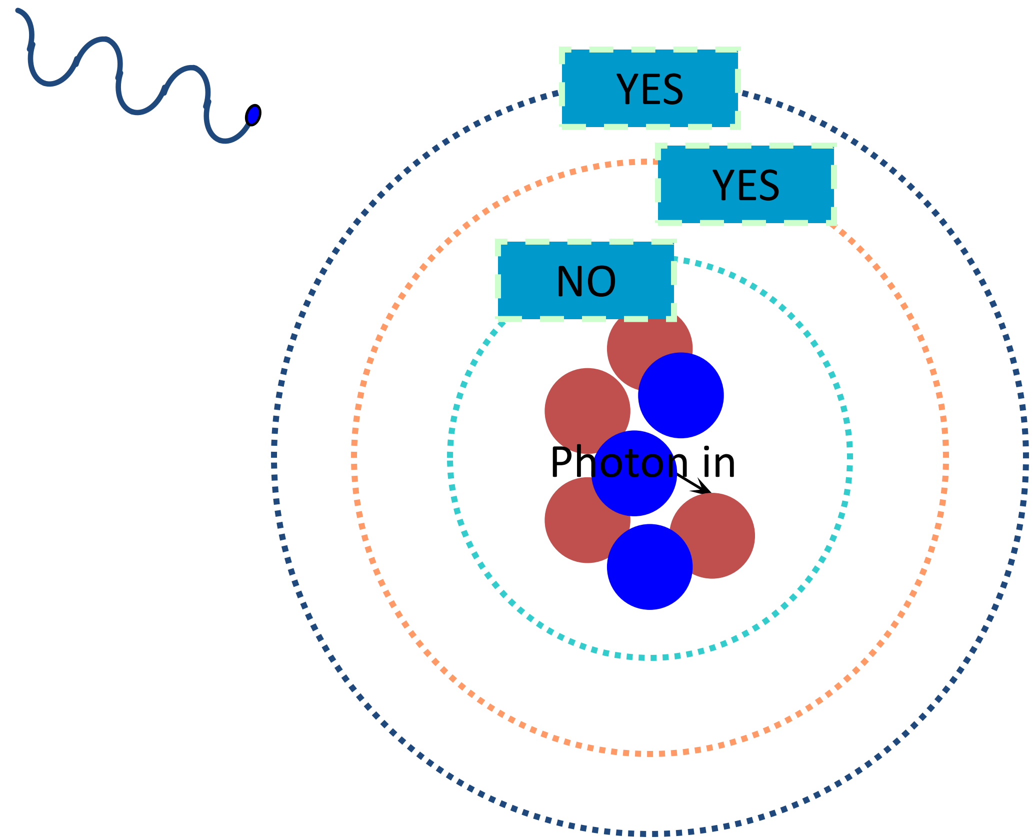


Which shells are candidates for photoelectric interactions?

Photoelectric Threshold

- Binding Energies
  - K: 100
  - L: 50
  - M: 20

Photon energy: 55

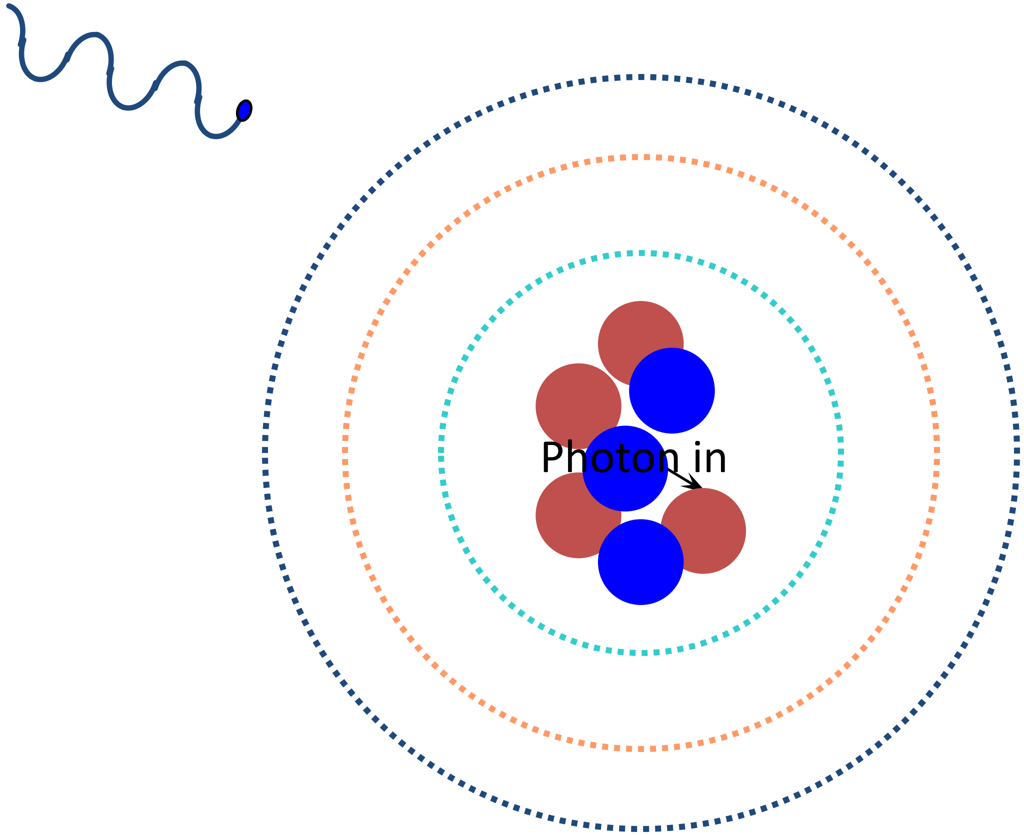


Which shells are candidates for photoelectric interactions?

Photoelectric Threshold

Photon energy: <u>105</u>

- Binding Energies
  - K: 100
  - L: 50
  - M: 20

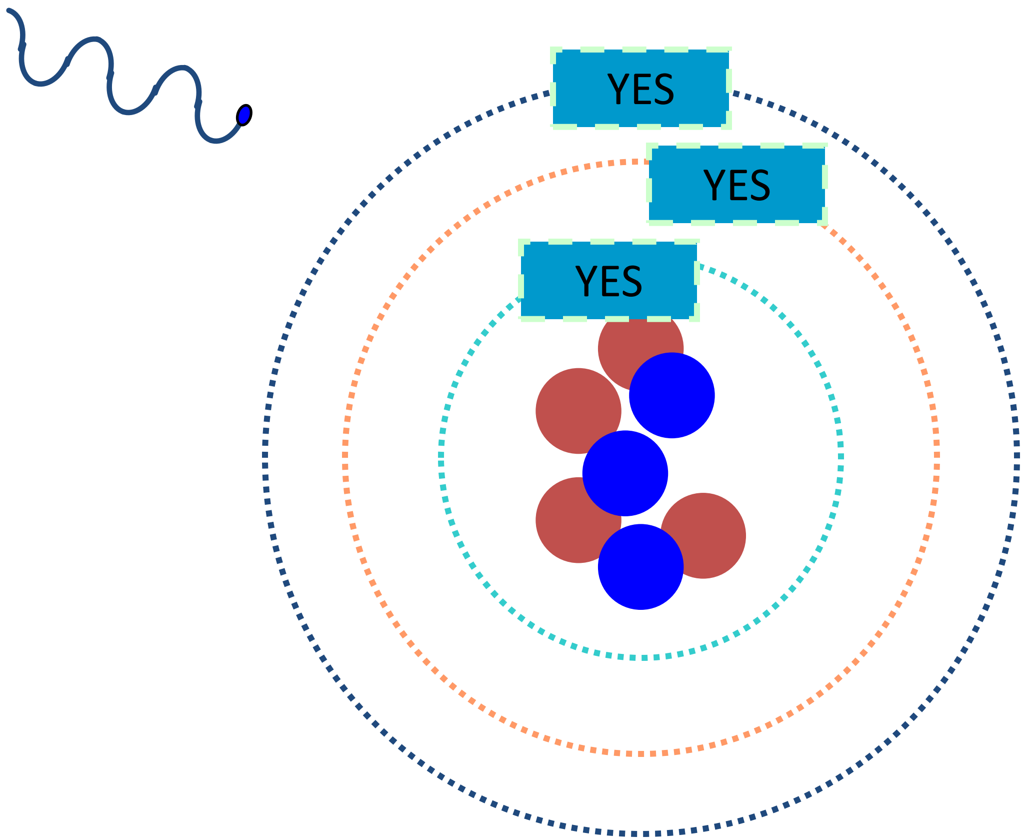


Which shells are candidates for photoelectric interactions?

Photoelectric Threshold

- Binding Energies
  - K: 100
  - L: 50
  - M: 20

Photon energy: <u>105</u>



Which shells are candidates for photoelectric interactions?

Photoelectric Threshold

$$\text{P.E.} \sim \frac{1}{\text{energy}^3}$$

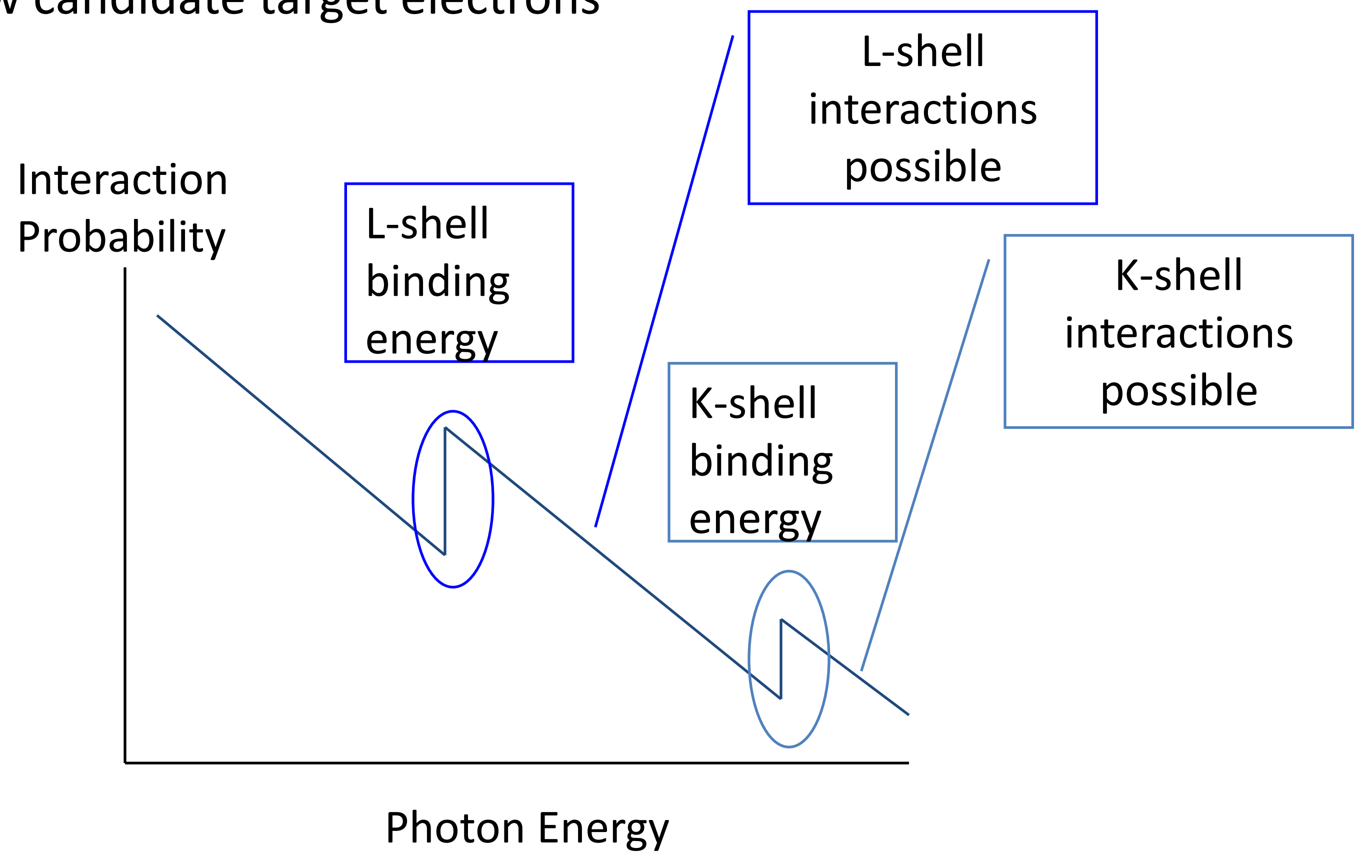
- Photoelectric interactions decrease with increasing photon energy

  BUT …

**

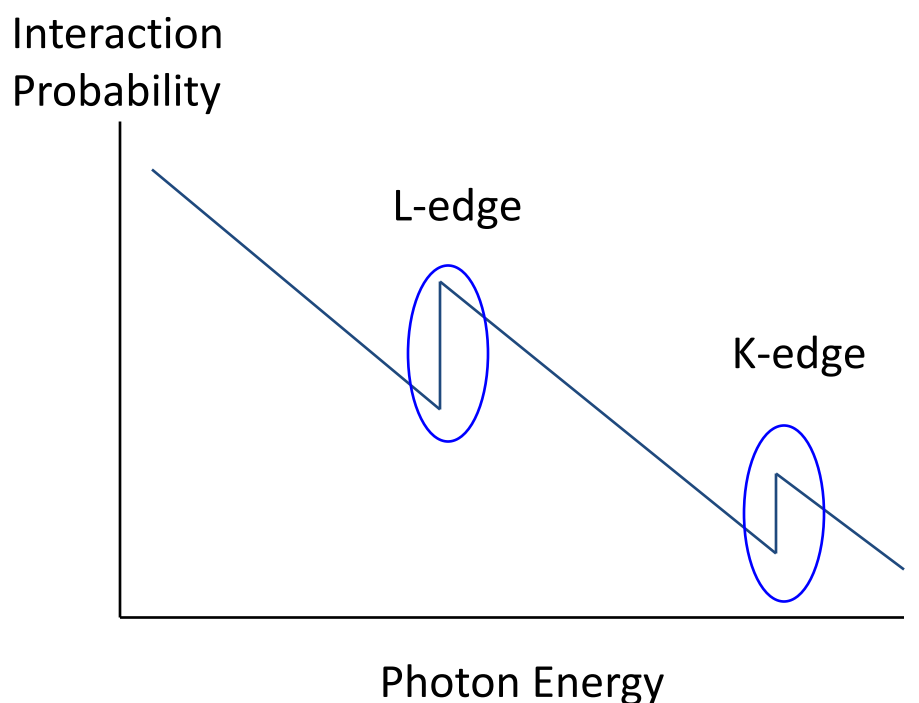
Photoelectric Threshold

- When photon energies just reaches binding energy of next (inner) shell, photoelectric interaction now possible with that shell
  - ♦ shell offers new candidate target electrons



Photoelectric Threshold

- causes step increases in interaction probability as photon energy exceeds shell binding energies = absorption edge



Absorption edge of an element = E_k of that element

The higher Z →the higher the E_k → the higher the absorption edge

Applications:

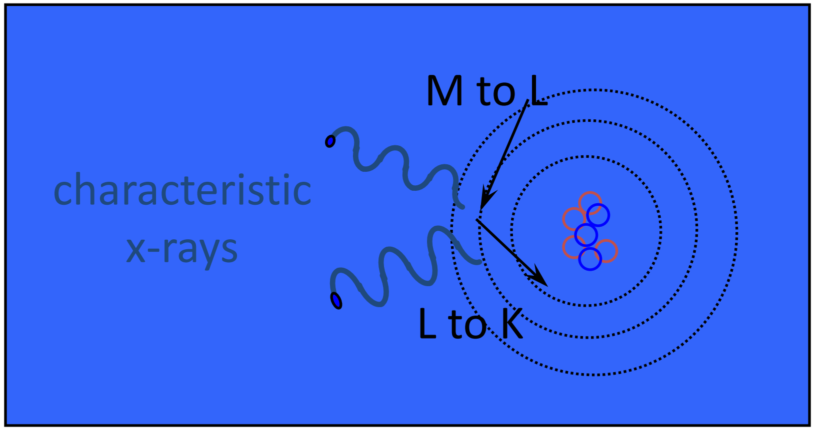
- 1)Iodine E_k = 33 kev

  This means that 31 kev photons are less attenuated than 35 kev photons
- 2)k-radiation (characteristic) of material is just less than E_k of that material → a material is relatively transparant to its own characteristic radiation
- 3)absorption edges of water , tissues , aluminum , bone are not significant (very low)

**

Results in Characteristic Radiation

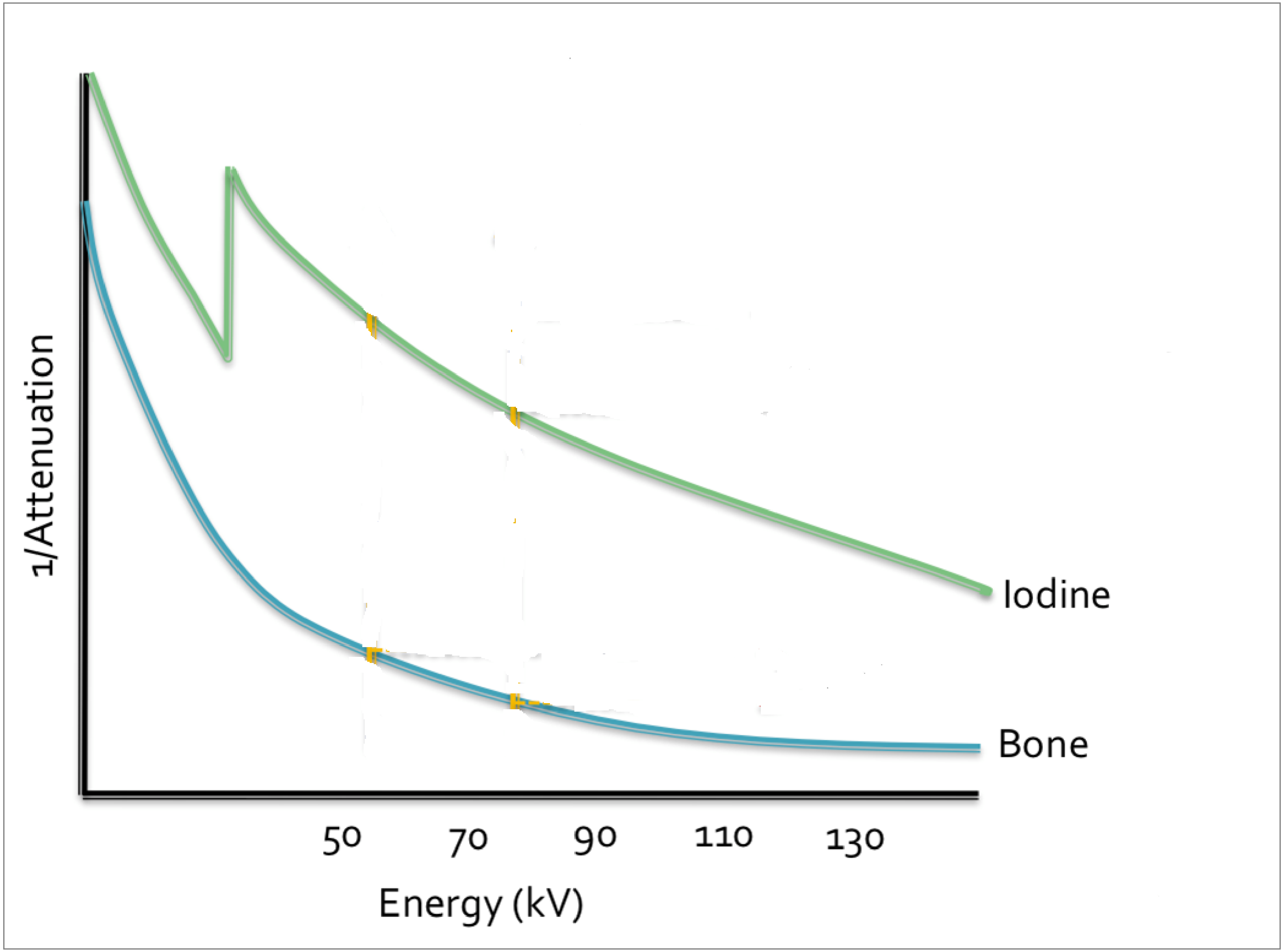
- electrons from higher states fall (cascade) until lowest shells are full
  - characteristic x-rays released whenever electron falls to lower energy state



Photoelectric Effect

Why is this important?

- photoelectric interactions provide <u>subject contrast</u>
  - variation in x-ray absorption for various substances
- photoelectric effect does <u>not</u> contribute to **scatter**


1/Attenuation
Iodine
Bone
50
70
90
110
130
Energy (kV)

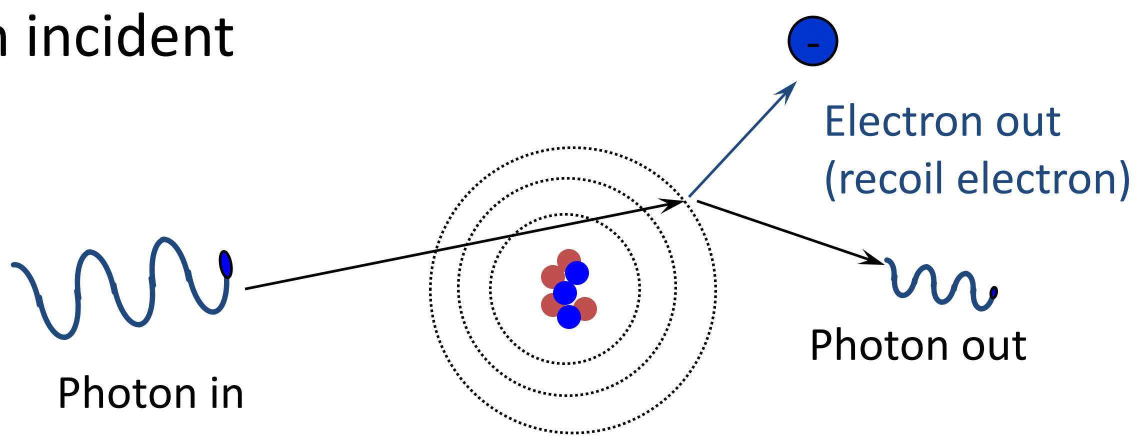
For molecules

- Photoelectric effect depends on Effective atomic number (average atomic numbers of constituent elements)
- Not dependant on molecular configuration

***

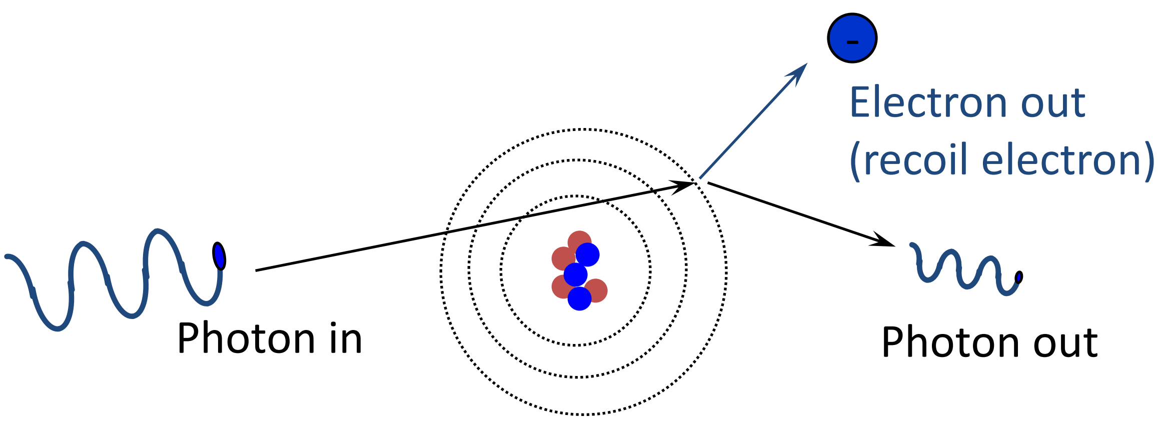
Compton Scattering

- Source of virtually all scattered radiation
- Process
  - – incident photon (relatively high energy) interacts with free (loosely bound) electron
  - – some energy transferred to recoil electron
    - electron liberated from atom (ionization)
  - – emerging photon has
    - less energy than incident
    - new direction



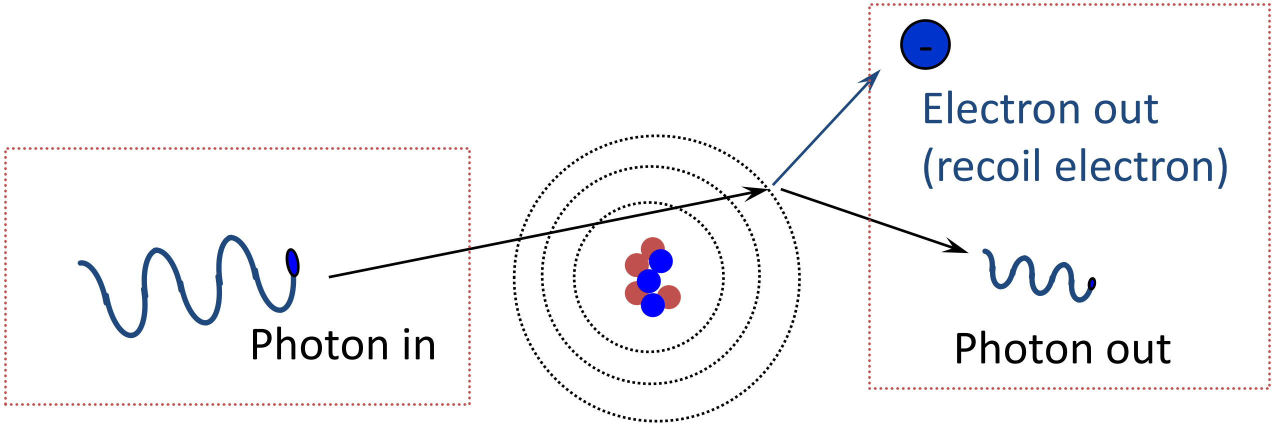
Compton Scattering

- What is a “free” electron?
  - low binding energy
    - outer shells for high Z materials
    - all shells for low Z materials



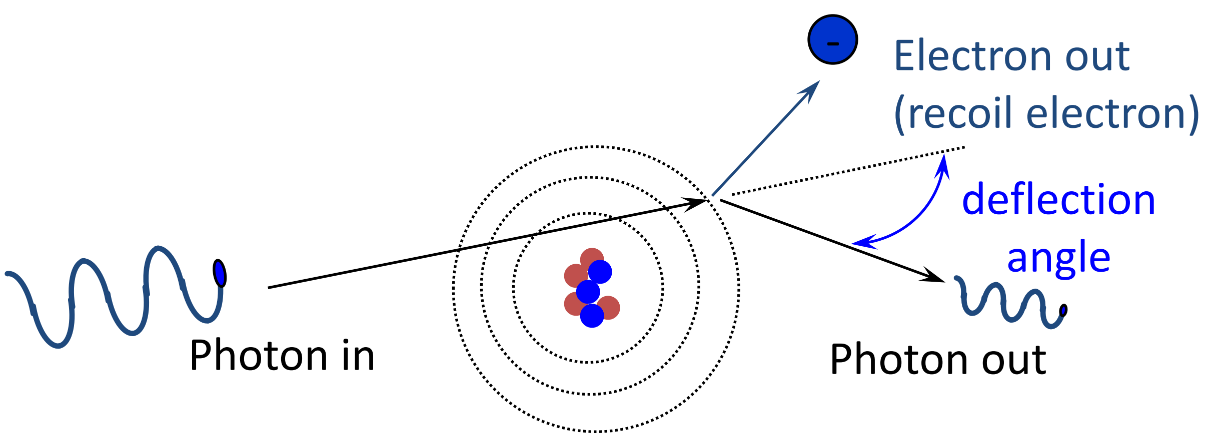
Compton Scattering

- Incident photon energy split between electron & emerging photon
- Fraction of energy carried by emerging photon depends on
  - incident photon energy
  - angle of deflection

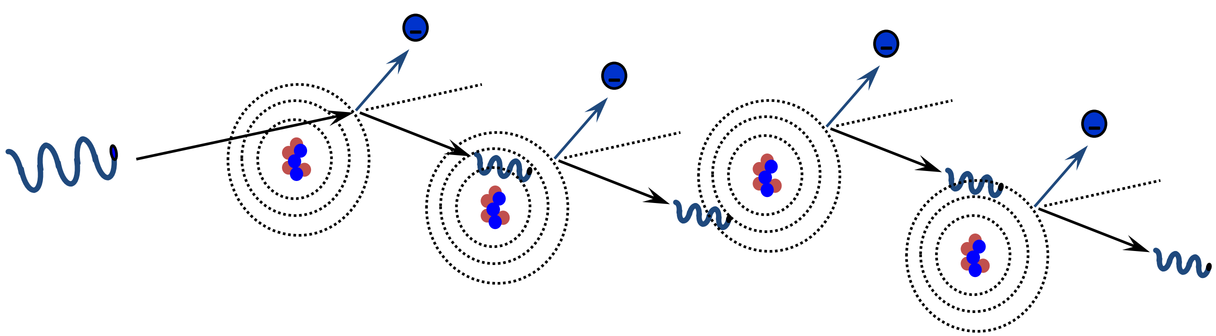


Compton Scattering & Angle of Deflection

- higher incident energy = less photon deflection
  - high photons primarily scatter forward
  - diagnostic energy photons scatter fairly uniformly
    - forward & backward
  - Low energy photons scatter backwards
- higher deflection = less energy retained
- photons having small deflections retain most incident incident energy



Compton Scattering & Angle of Deflection

- Photons having small deflections retain most incident incident energy
- Photons will scatter many times, losing a little energy each time.
- Photons are scattered in all directions , electrons are projected only sideways and forward
- 

Compton Scattering

- Formula

$$\Delta \lambda = 0.024\ (1\text{-cos}\ \Theta)$$

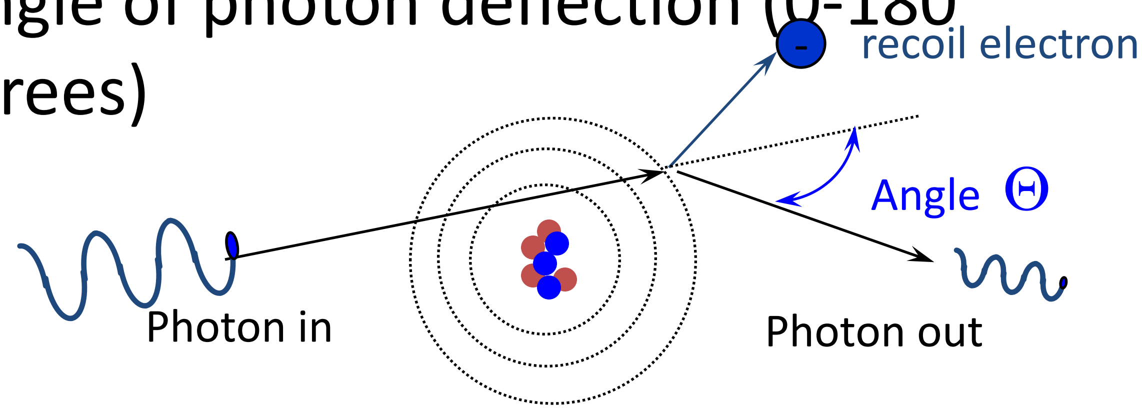
0^o results in no change in wavelength

180^o results in maximum change in wavelength

where

$\Delta \lambda$ = change in wavelength (A) for photon

Θ = angle of photon deflection (0-180 degrees)



Compton Scattering Probability of Occurrence

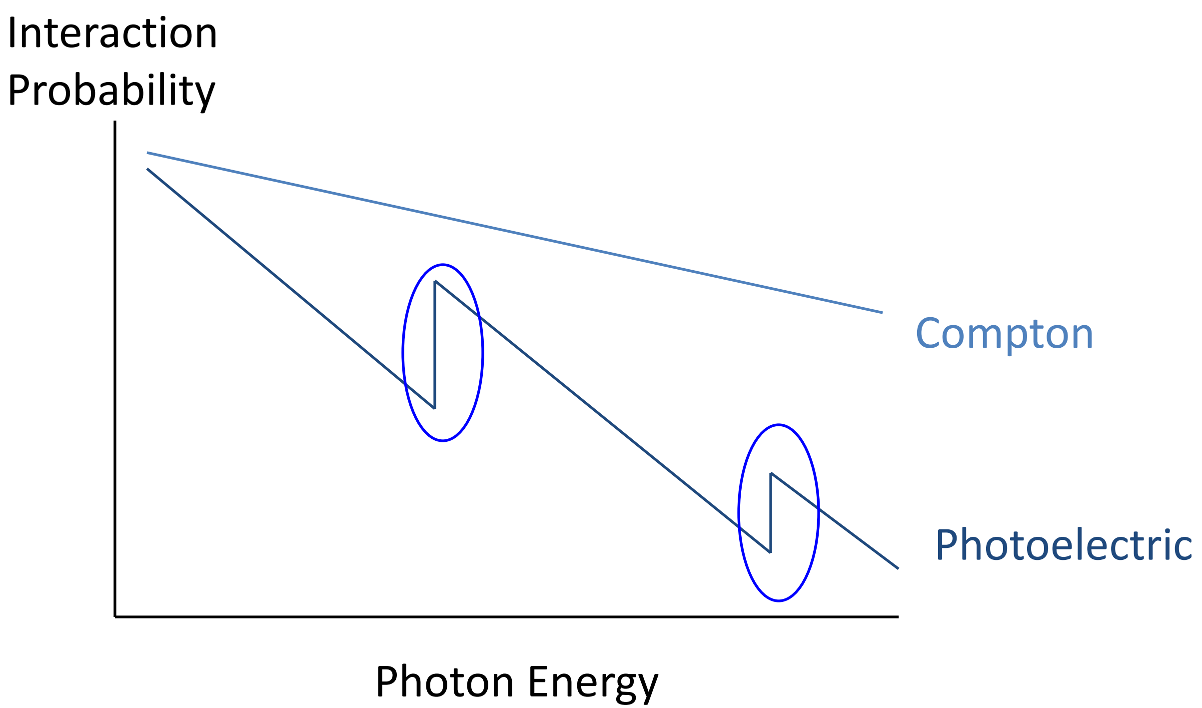
- independent of atomic number
- Proportional to electron density (electrons/gram)
  - fairly equal for all elements except hydrogen (~ double)
- proportional to the physical density (as all attenuation processes)
- Decrease only slightly with increase in energy (proportional to 1/E)

ELECTRON DENSITY

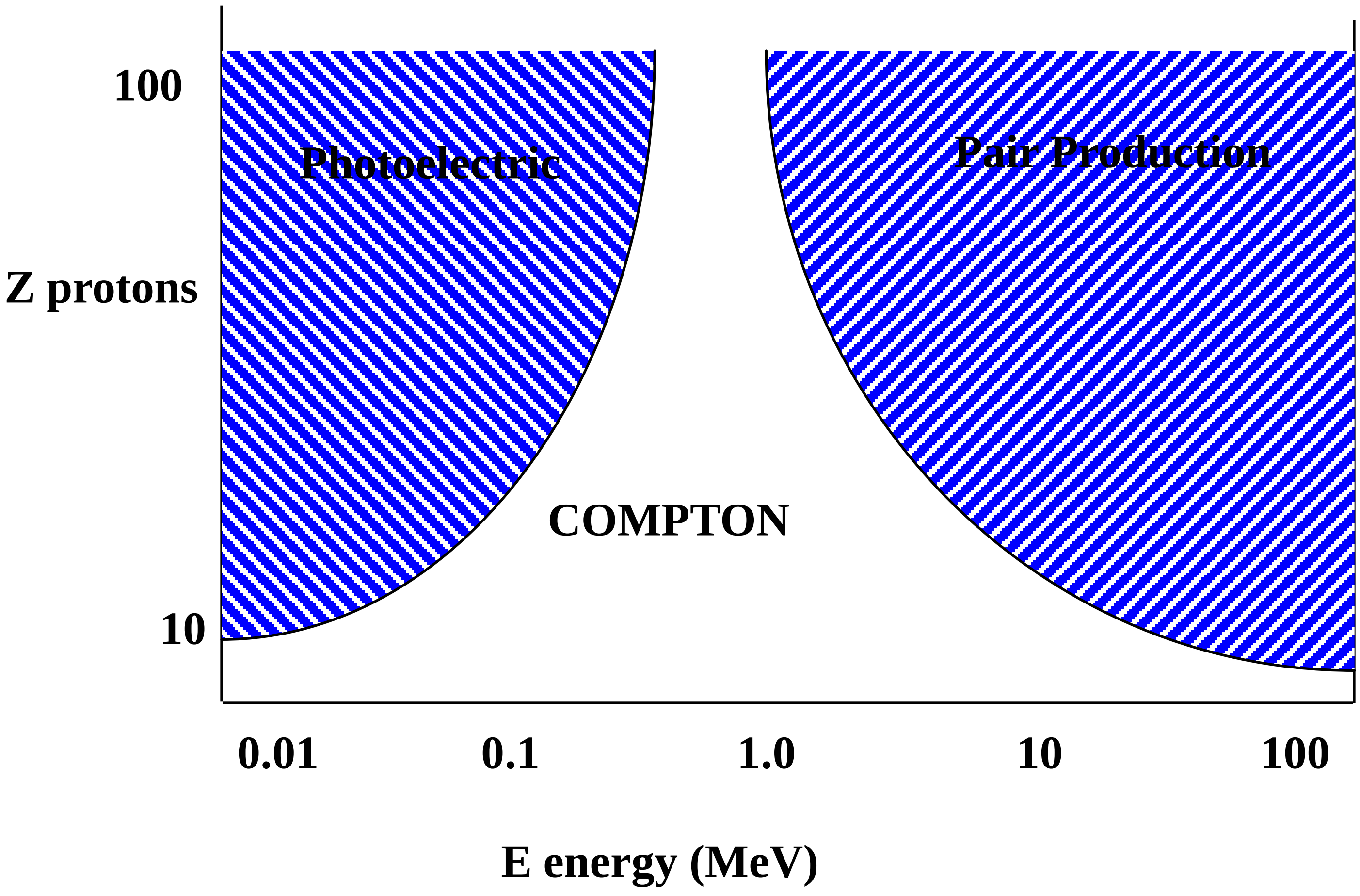
- The number of electrons in a unit volume
- α 1/A
- α Z
- α Z/A
- Z/A for all elements (except hydrogen) ≈ 0.5
- Very small variations between elements

Compton Scattering Probability of Occurrence

- decreases with increasing photon energy
  - decrease much less pronounced than for photoelectric effect



Photon Interaction Probabilities



- Applications:
- 1)photoelectric absorption is more important than compton for high Z material and low E photons
- 2) compton process is more important than photoelectric absorption for low Z material and high E photons

Effect of Z

For diagnotic energy range:

- compton process is predominant for air, water and soft tissues
- photoelectric absorption is predominant for contrast media , lead and film
- both are important for bone

Secondary electrons and ionization

- Secondary radiation = compton scattered radiation
- Secondary electrons = recoil electrons (from compton) + photoelectons (from photoelectric effect)
- Secondary electrons:

1)Ionize and excite the surrounding atoms

2)In air : the electron loses 34ev to ionize an atom (to form an ion pair)

3)When it lose all of its energy in this way , it comes to the end of its range

4)The range increase with :increasing electron energy
decreasing material density

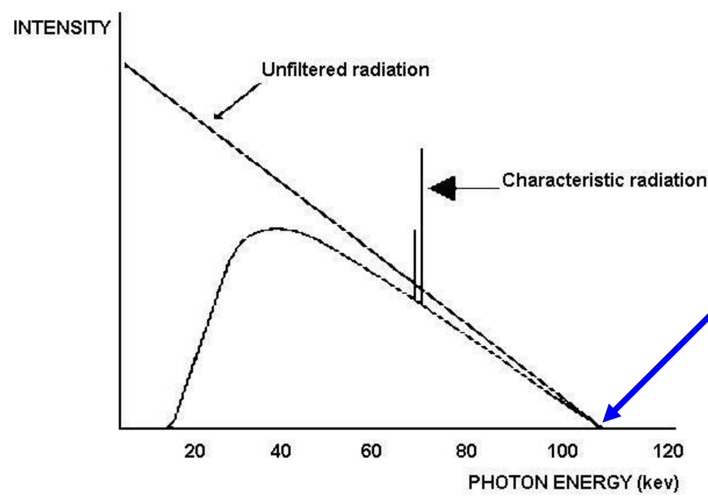
5)Excitation and ionization produced by the secondary electron is responsible for : measurement of radiation , hazards of radiation , luminescence , and film image formation

- This means that xray and gamma rays are indirectly ionizing (other EM waves are non ionizing with small exceptions)
- α and β radiations are directly ionizing

Filtration

- X-ray beams from tubes
  - **Polychromatic**
    - Brehmstrahlung
    - Characteristic
  - spectrum of energies from 0 – kVp set on generator
- average beam energy

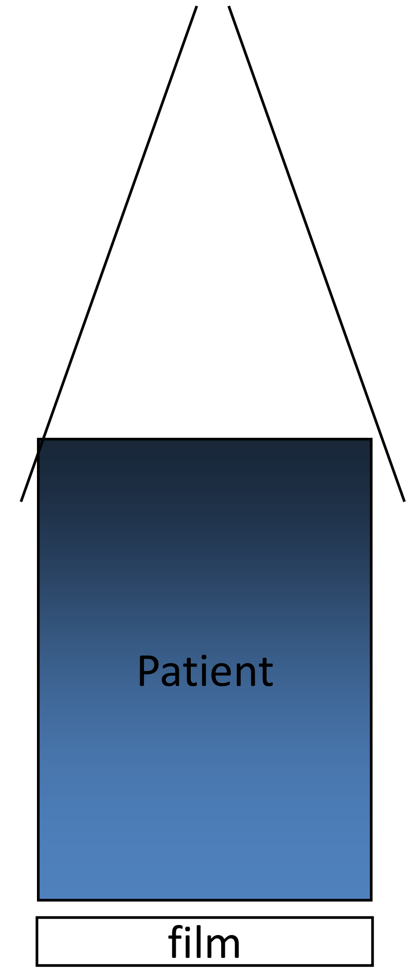
  1/3 to 1/2 of peak (kVp)



kVp
(as set on
generator)

Unfiltered Beams

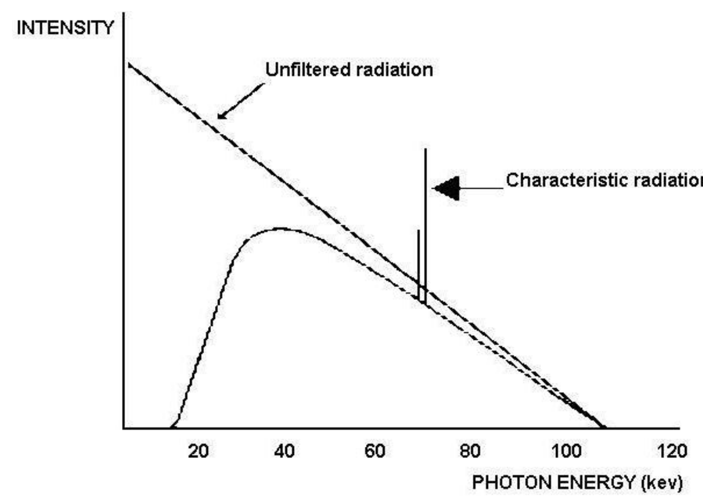
- most energy deposited in first few centimeters of tissue
  - lowest energy photons selectively removed
- energy of low energy photons
  - contributes to dose
  - does not contribute to image
    - photons don't reach film



Ideal Filtration

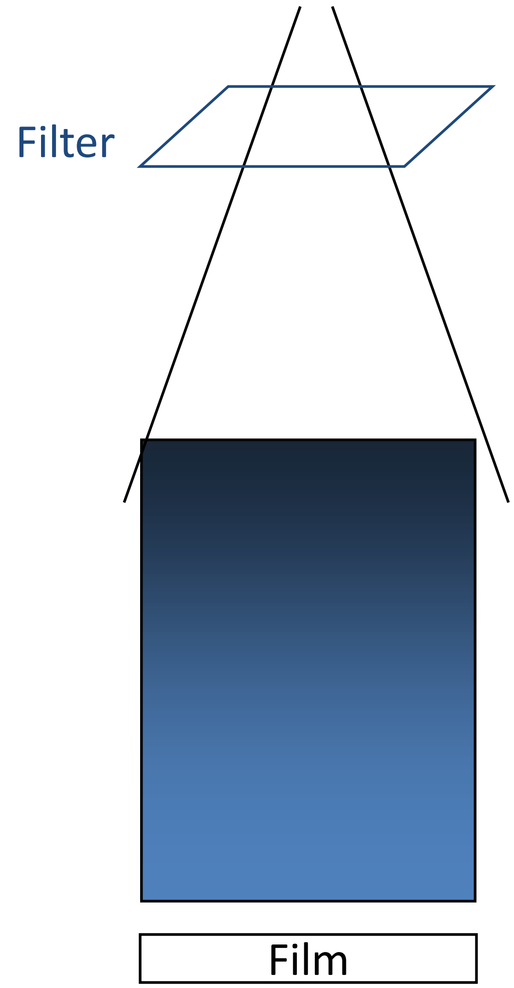
- absorption characteristics
  - absorbs all low energy radiation
  - absorbs no high energy radiation
- high atomic number desirable

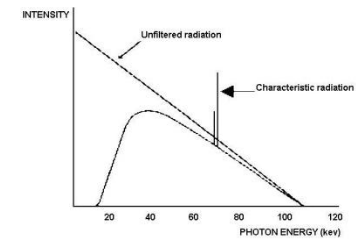
  →increases photoelectric absorption of low energy photons
- Not too high (or useful x ray will be absorbed)



Filter’s Function

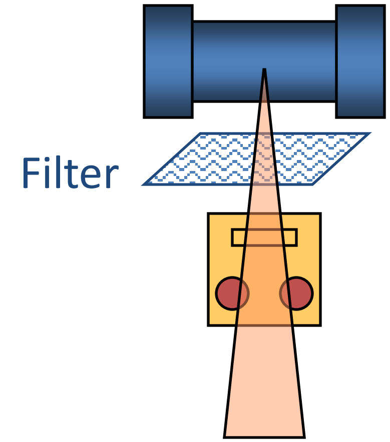
- shape beam’s energy spectrum
- selectively attenuate low energy photons
  - less low energy radiation incident on patient
  - energy deposited in filter, not in patient



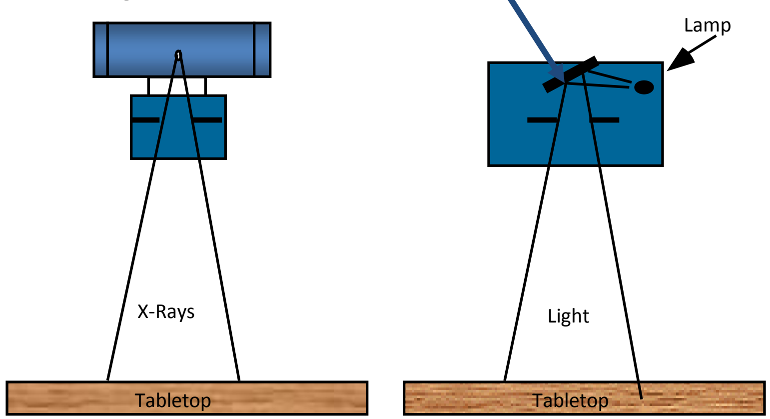


Filtration Locations

- x-ray tube and housing
  - **inherent filtration**
- metal sheets placed in beam path
  - placed between tube and collimator or in collimator
  - Usually aluminum
  - **added filtration**

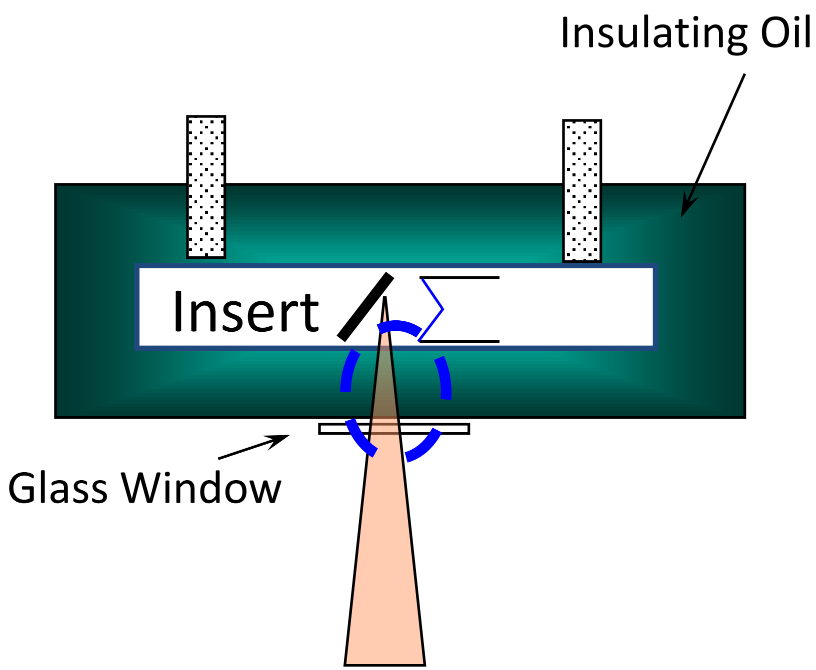


- collimator mirror
- table (for under-table tube fluoro)



Inherent Filtration

- Absorption of x-rays by tube
  - glass insert
  - insulating oil
  - housing window

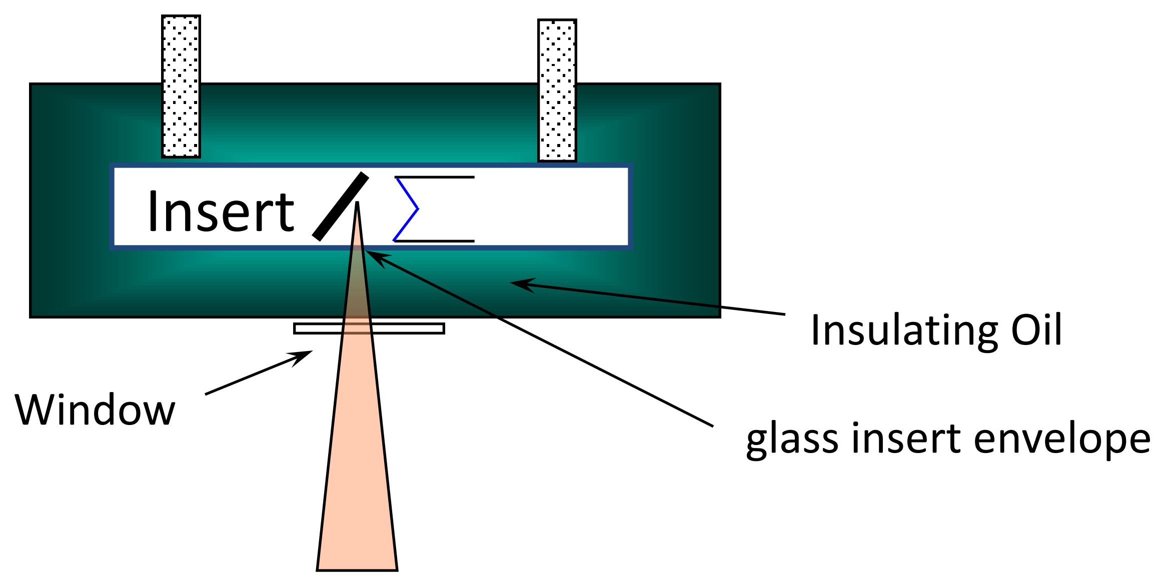


Inherent Filtration

- Typical Inherent Filtration

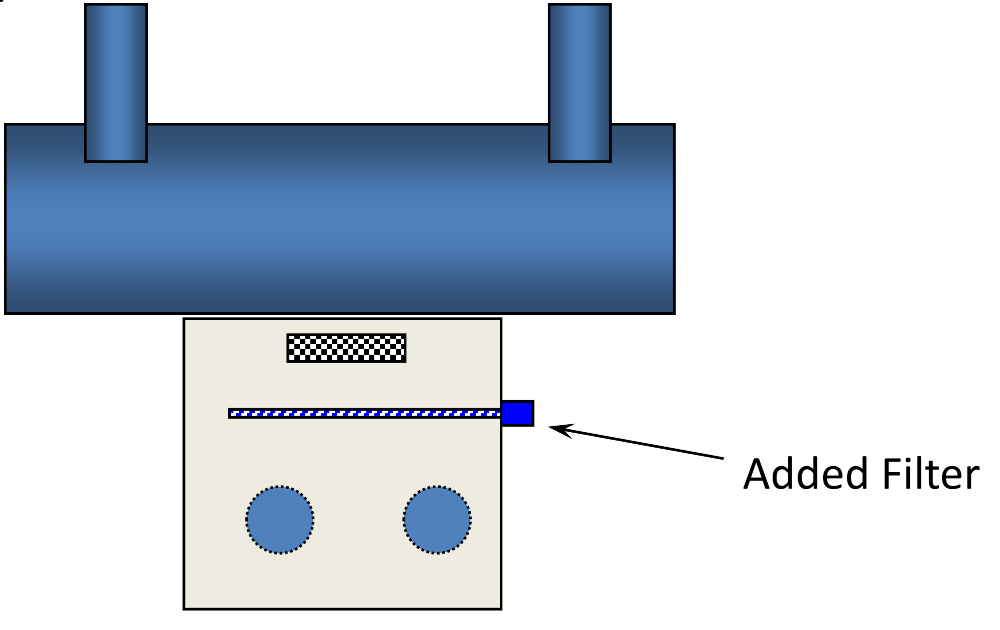
  1.0 mm aluminum equivalent

  – mostly due to glass insert envelope



Added Filtration

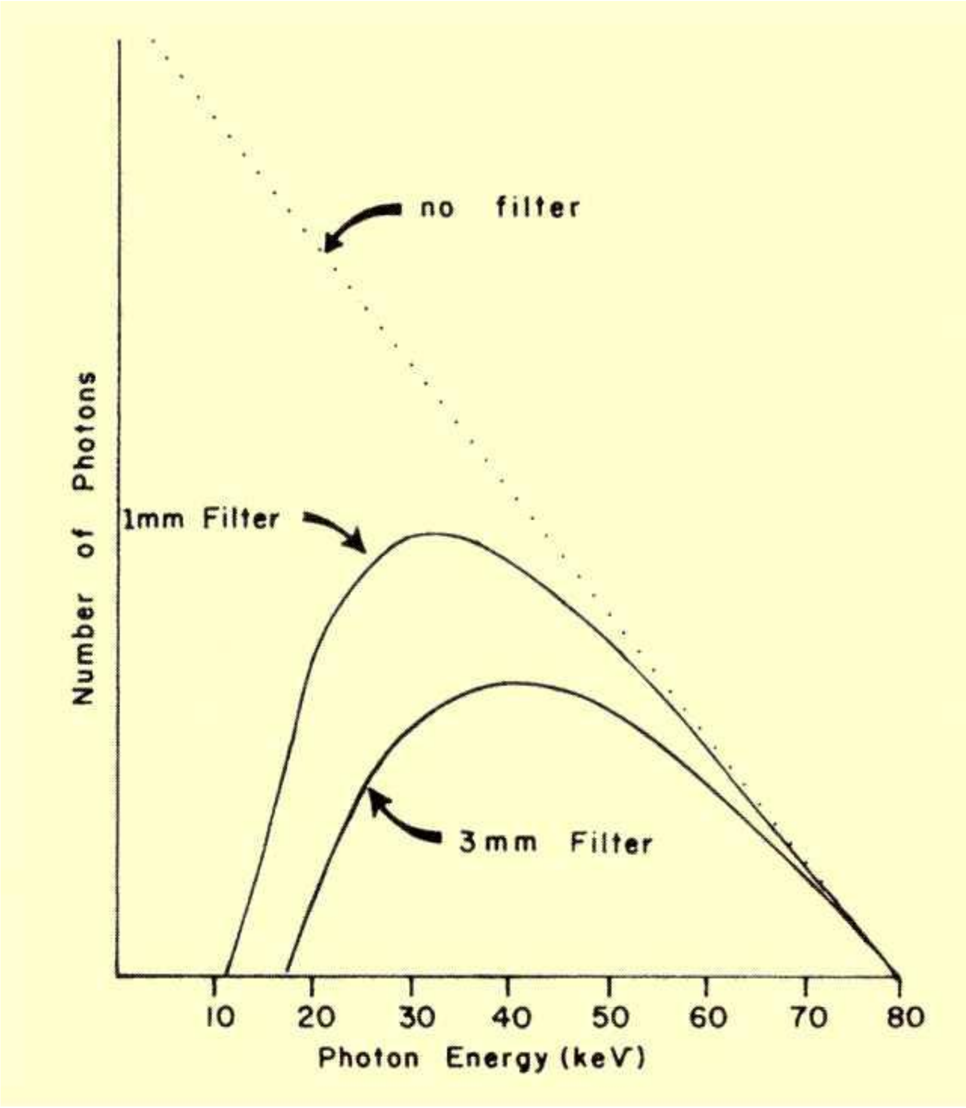
- Filtration intentionally added by placing metal plate in collimator
- The main attenuation process of the filter is photoelectric effect
- It will remove low energy photons more than high energy photons ($\alpha 1/E^3$)



- Total filtration = Inherent Filtration + Added Filtration
- It must be about 2.5 mm at 70 kev
- → added filtration = 1.5 mm aluminum
- inherent filtration undesirable in mammography
  - Beryllium (Z=4) often used for exit portal (window) of glass envelope
  - beam essentially unfiltered

Filtration Effects

- decreases beam intensity (total x ray output)
- increases mean beam energy (=effective energy = quality) as it attenuate low energy photons more than high energy photons
- In other words :increase HVL of the beam = penetrating power
- Reduce skin dose & have little effect on the image (increase film dose : skin dose ratio)
- Increase the low energy cut-off (spectrum move to the right)
- DOES NOT affect maximum energy

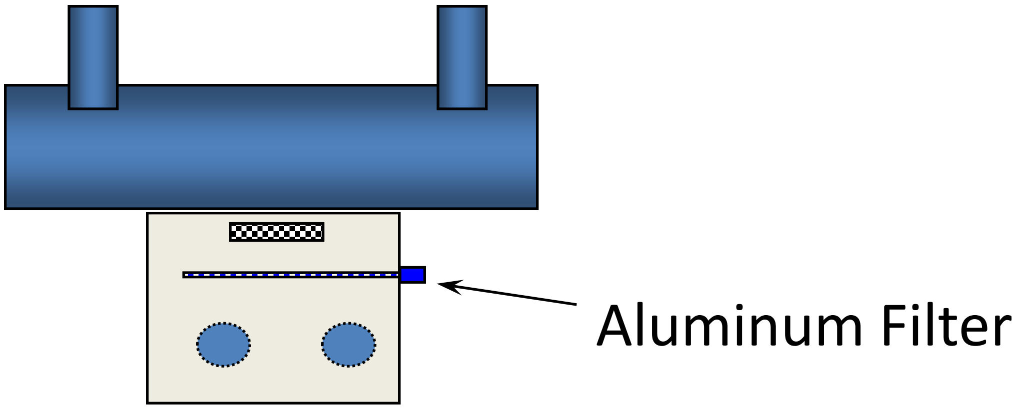


Excessive Filtration

- Decrease output without further improvement in patient’s dose
- Decrease x-ray output may require increase in exposure time (patient’s movement will become a problem) and increase in mA (results in excessive tube heating)

Practical Filters

- Aluminum(Z=13)
  - Most common
  - atomic # 13
  - inexpensive
- copper(Z= 29)
  - but must be used with backing aluminum filter on patient side..why?
    - aluminum absorbs copper's 8 keV characteristic radiation

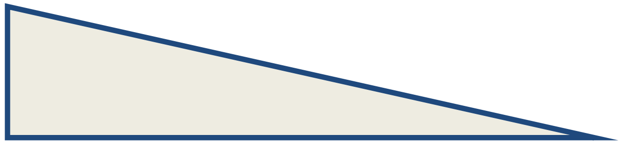


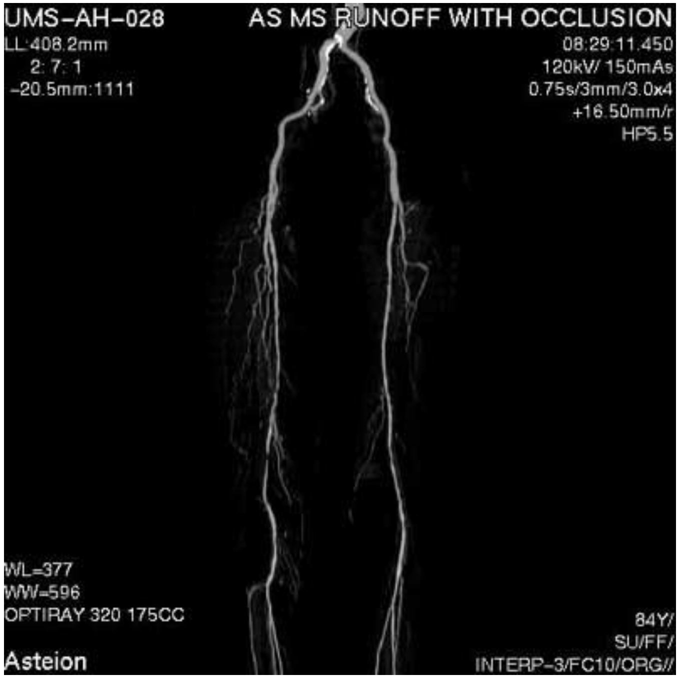
Filters: The Good & Bad

- Disadvantages
  - reduces beam intensity
  - increases
    - tube loading
    - exposure time
      - patient motion
- Advantage
  - gross reduction in patient dose
    - 80% typical

Wedge Filters

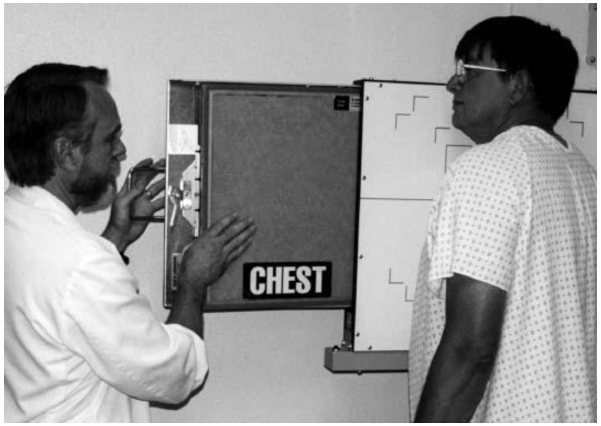
- thickness varies
  - filter shaped like wedge
- application
  - used to obtain uniform film density when large change in patient thickness over image field
  - Prevent flaring of image at edges of the film
    - e.g. long-leg angiography

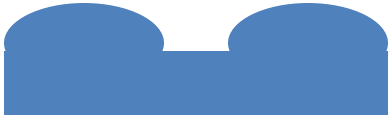




Wedge Filters

- chest filters
  - contoured for lung fields





For k-edge filters …. See mammography

Half Value Layer

- Depends upon
  - kVp
  - waveform (single/three phase)
  - inherent & added filtration

kVp	HVL (mm Al)
30	0.3
40	0.4
49	0.5
50	1.2
60	1.3
70	1.5
71	2.1
80	2.3
90	2.5
100	2.7
110	3.0
120	3.2
130	3.5
140	3.8
150	4.1

THANK YOU